FOREST PRODUCTS JOURNAL

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Designing hyperbolic paraboloids of wood—Some engineering factors involved.

Vol. X, No. 9

1960/SEPTEMBER

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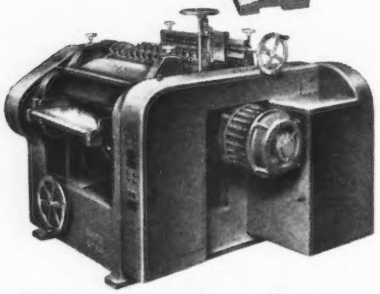

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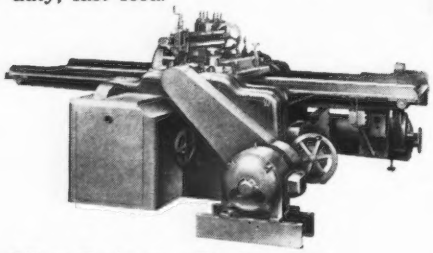

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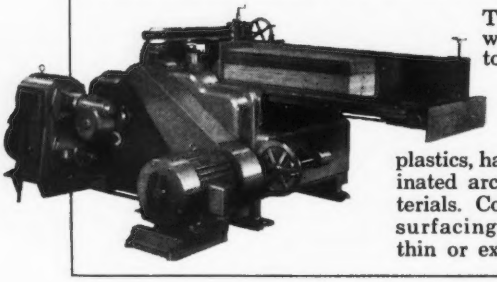

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FOREST PRODUCTS JOURNAL

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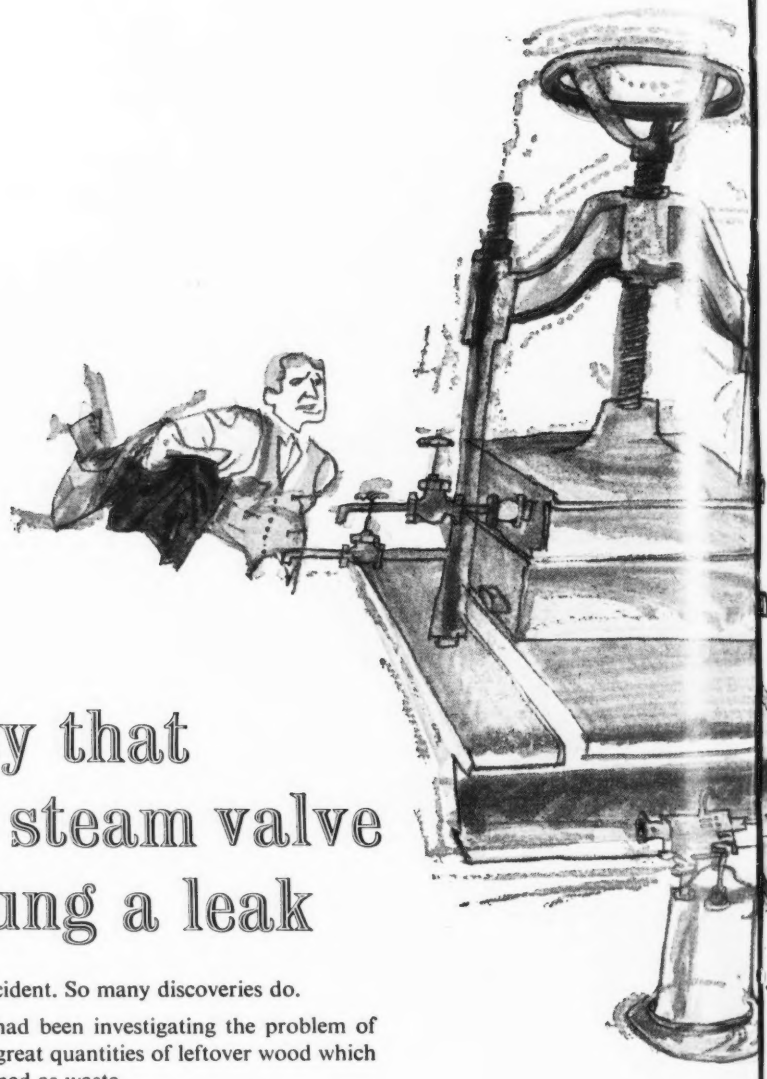

the day that Mr. Mason's steam valve sprung a leak

It started with an accident. So many discoveries do.

William H. Mason had been investigating the problem of what to do with the great quantities of leftover wood which sawmills usually burned as waste.

By a unique explosion process, he had discovered how to reduce the wood to its strong, component fibers.

But he didn't really find hardboard until the day his steam valve sprung a leak.

He had built a small forming machine for making wetlap. Placing some of the wetlap in a steam-heated screw press, he intended to squeeze out the water and then dry the board in an oven.

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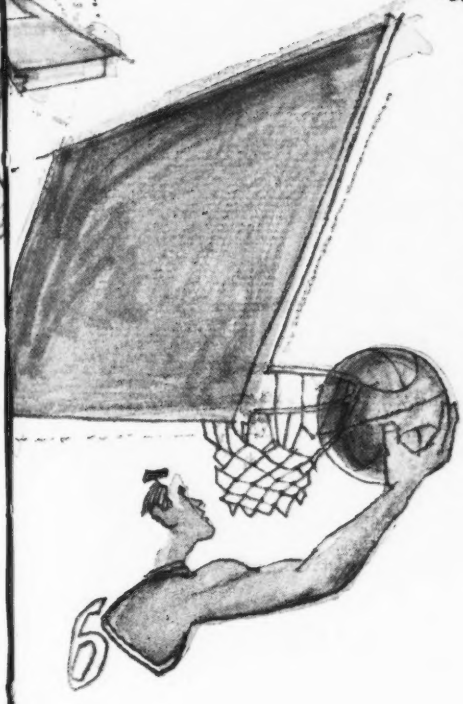
Since that time, the uses for Masonite hardboard have become practically limitless. It is found everywhere in the home furnishings field: as walls, doors, ceilings, siding, and in almost all types of furniture.



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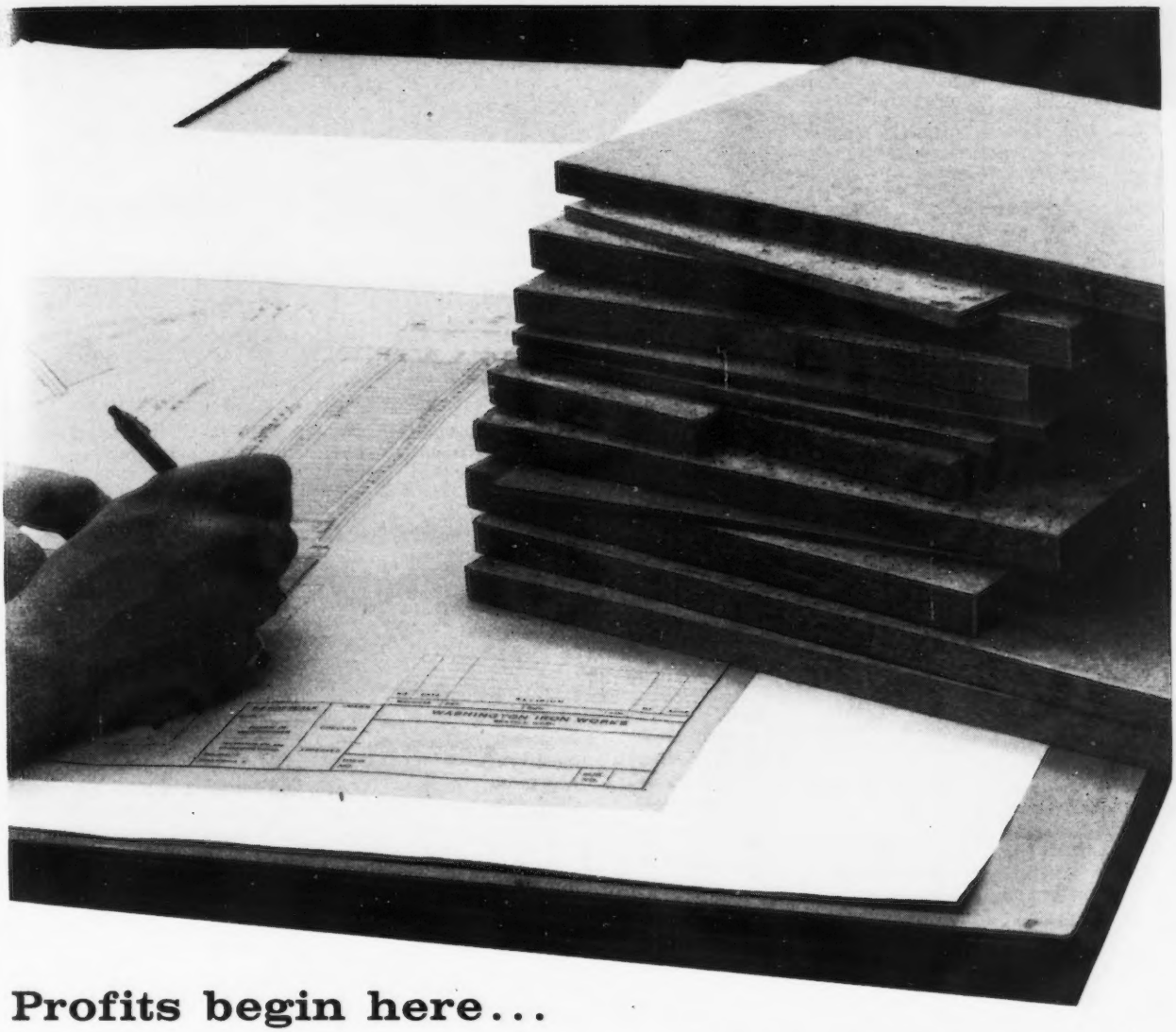

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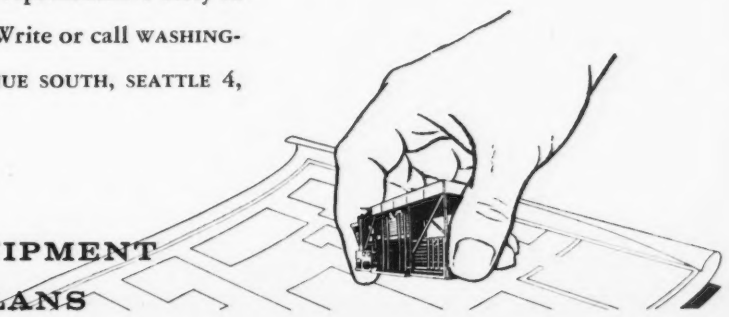

WASHINGTON PRESS EQUIPMENT HAS A PLACE IN YOUR PLANS

Important FPRS Dates

September 28–October 1: Midsouth Section Meeting, Memphis, Tenn.
October 13–14: Ohio Valley Section Meeting, Evansville, Ind.
October 14–15: Northeast Section Meeting, New Haven, Conn.
October 16–17: Executive Board Meeting, Madison, Wis.
October 16–22: National Forest Products Week, Nation-Wide.
October 17–18: Pacific Northwest Section Meeting, Tacoma, Wash.
October 19: Great Lakes Section Meeting, Grand Rapids, Mich.
October 20–21: Upper Mississippi Valley, Section Meeting, St. Paul, Minn.
October 21: Northern California Section Meeting, Stockton, Calif.
October 27–28: Midwest Section Meeting, Madison, Wis.

Wood Machining Abstracts Available for 1958–1959

The Committee on Recent Wood Machining Literature, a sub-division of the former Wood Machining Division, has again compiled an annual report that contains significant abstracts selected from world sources on the subject of wood machining.

The abstracts are designed to help interested persons locate recent publications in the field. The first report, published for the years 1957–1958, has achieved status as an authoritative source, and hundreds of copies have been distributed on request throughout the world.

This year's 19-page report is divided into two sections. Section 1 contains a list of 30 world-wide sources of wood machining information.

Section 2 contains abstracts grouped according to general subject matter. They cover special equipment and techniques used in research, conferences and industrial directories; wood machining standards, veneer cutting, circular saws, band saws, frame saws, and planing.

The committee consists of C. W. McMillin, American Machine & Foundry Co.; R. J. Hoyle, Potlatch Forests, Inc.; N. C. Franz, University of Michigan; Lawrence Leney, University of Missouri; and Richard Perkins, State University College of Forestry, N. Y.

Single copies are available on request to Forest Products Research Society, Reader Service, 417 North Walnut St., Madison 5, Wis. Additional copies are available at 50 cents each.

Pulp and Paper Foundation Awards Scholarships

The Scholarship Committee of the Pulp and Paper Foundation, Inc., has awarded scholarships totaling $32,500 in the School of Forestry at North Carolina State College for the 1960–61 academic year. Announcement of the committee's action was made by Dr. R. J. Preston, dean of the college's School of Forestry, and Prof. R. G. Hitchings, faculty member of the Pulp and Paper Technology Curriculum in the School of Forestry.

FPRS News-Digest

Section Meetings To Honor National Forest Products Week

At least 6 FPRS Sections have planned their fall meetings to honor National Forest Products Week, October 16–22, a week sponsored by the lumbermen's fraternity, Hoo-Hoo International, to support the National Wood Promotion Program.

"Know Your FPL"

The **Midwest Section** will hold its meeting in Madison, October 27 and 28, in cooperation with the U.S. Forest Products Laboratory. K. E. Kimball, secretary-treasurer, reports that the theme of the first day's session will be "Know Your FPL," conducted in honor of the Laboratory's Golden Anniversary. The morning session will consist of a resumé by each division chief of his phase of the laboratory's research program. Included in the afternoon session will be a panel discussion in which the head of the various divisions and their key personnel will be available to answer questions from FPRS member and guests.

On October 28, the topic of the session will be "Marketing Lumber Today." James Elf, National Starch Products, Inc., Chicago, is the chairman. The speaker of the official luncheon, scheduled for 12:30 has not been named. The program will be concluded with a tour of the laboratory.

"What the User Expects"

Wayne Meek, chairman of the **Upper Mississippi Valley Section,** has announced that the theme of his section's meeting, to be held October 20 and 21, at St. Paul, is "What the User Expects of Wood Products." The meeting will take place at the School of Forestry, University of Minnesota. Participants will tour the new Forest Products Building at the School of Forestry. Speakers, panel members, and other details will be announced later.

"Prefabs and Components"

The **Northern California Section** meeting will be held at Stockton, Calif., on October 21, reports Victor S. Roth, vice chairman and program director. Highlights of the program will include talks by Lewis J. Lewellen, National Homes Corporation, Newark, Calif., on prefabrication; Evan Jeffreys, Idaco Lumber Co., Healdsburg, Calif. on precutting, and Lee Doud, Doud Lumber Co., San Jose, Calif., on components from the retailer's point of view. E. P. Ivory of Ivory Pine Co., Dinuba, Calif. will moderate. Tours of the California Cedar Products Co. and the McCormick & Baxter Creosoting Co. will be conducted in the afternoon, followed by a cocktail party and banquet, featuring a speech by A. B. Hood, Ralph L. Smith Lumber Co., and vice-president of National Lumber Manufacturers Association.

"To Buy or Not to Buy"

Grand Rapids, Mich., is the scene of the **Great Lakes Section** meeting, October 19. The technical session will center around the theme, "To Buy, Or Not To Buy," a discussion of how to develop an economic evaluation of new plant equipment. The honored guest and dinner speaker, will be Raymond H. Berry, president of FPRS.

"Wood in the Golden '60's"

The Yale School of Forestry will host the **Northeast Section's** meeting, October 14 and 15 in New Haven, Conn. J. Allan Hauter, chairman, has announced that the general theme is "What Do the Golden '60's Hold For Wood?" A cocktail hour, banquet, business meeting and a nationally-known speaker will be features of the program planned for Friday evening at the New Haven Lawn Club. A tour and demonstrations at Yale's New Greeley Memorial Laboratory will be held Saturday morning, and that afternoon, all registrants will cheer for Yale against Cornell in the Yale Bowl.

"Research for Wood's Survival"

"Research for Wood's Survival in the Market Place" is the theme of the **Mid-South Section** meeting, September 28 to October 1 in Memphis, Tenn., according to R. D. McCrite, chairman. The distinguished speakers and varied entertainment planned for this meeting were reviewed in the July issue of the Forest Products Journal.

Other sections that are planning meetings during National Forest Products Week are the **Pacific Northeast Section,** Tacoma, Wash., October 17 and 18; and the **Inland Empire Section,** October 21 and 22.

STUDENTS AT THE WOFI FINISHING SEMINAR exchanging ideas during a coffee break are (l. to r.): W. C. Lowe, Jr., Alma Desk Co.; James Wedding, Imperial Desk Co., a North Carolina student observer; Robert E. Bayles, Boling Chair Co.; and Rex Davis, The Lane Co.

EXAMINING A NEW FINISHING TECHNIQUE on a desk panel are (l. to r.): James Wedding; Professor E. Sigurd Johnson, North Carolina State College; Joyn Whiteside, The Lilly Co.; John L. Thornbury, Jasper Lacquer Co.; and Professor Ray Carter, North Carolina State College.

THE LATEST FINISHING EQUIPMENT and methods of application are explained by an instructor to (l. to r.): Robert W. Bayles, Boling Chair Co.; James Wedding, Imperial Desk Co.; Charles Overstreet, The Lane Co.; and Rex Devis.

Finishing School Spawns 28 Ideas

Sixty days after the close of the Finishing Seminar, sponsored by the Wood Office Furniture Institute at North Carolina State, an evaluation study of 17 "students" who attended revealed 28 practical ideas at work, as the result of the course. Plant superintendents, engineers and finishing foremen examined subjects ranging from wood preparation and sanding, to improved methods, such as airless spraying and coating machines. New methods of sanding, quality control and Polyesters were treated in the classrooms and the laboratory.

This Seminar, the second WOFI sponsored cost-reduction "short course," was especially designed for Institute member companies. A new course will be announced for 1961.

Junior Scientists Help U. of C. Lab Men

Six outstanding California youth have been serving during the summer as "junior associates" of top-flight wood technologists on research projects being conducted at the University of California's Forest Products Laboratory in Richmond.

The young men, who were picked from the cream of California high school students for the "research participation" program which is supported by the National Science Foundation, are Jeff Kane, 16, Hollister; Don Zwakenberg, 17, Pittsburg; Jim Disbrow, 17, Vallejo; Brad Southworth, 16, San Leandro; Paul Bagley, 17, El Cerrito; and Charles Kimble, 16, Benicia.

In the Laboratory, Zwakenberg is helping Dr. David L. Brink, associate chemist, to develop a new wood pulping process, and Bagley is testing wood glues under the guidance of Carl W. Maxey, laboratory technician in wood technology.

Kane is probing the mysteries of wood extractives with Dr. Arthur B. Anderson, project leader in wood chemistry, while Disbrow is assisting Dr. Gordon Nichols, research associate from New Zealand, in a study of wood particle board.

Young Southworth is investigating the problem of shrinkage in hardwoods during seasoning with Dr. Eric L. Ellwood, project leader in timber physics, and Kimble in aiding Mrs. Addie S. Wong, laboratory technician in wood chemistry, to identify the chemical properties of stain in redwood.

Pre-logging With a Portable Steel Spar

An experiment conducted recently by the Vancouver Laboratory, Forest Products Laboratories of Canada in co-operation with a large west coast logging company, showed that pre-logging with a portable steel spar on rough steep ground promises an increase in the quality and quantity of material recovered from the multiple-storied cedar–hemlock–balsam stands, typical of many of the west coast logging areas.

Pre-logging is practical only on a multiple-storied stand containing a substantial volume in the smaller diameter classes which suffer extreme breakage when felled in a one-step operation. This method would attain its maximum value when high quality material such as poles and piling can be included in the pre-log material.

At the experimental area, all trees 22 inches d.b.h. and under, as well as the smaller merchantable snags and windfalls were removed in the pre-logging operation. This accounted for approximately 70 per cent of the standing trees and 30 per cent of the available volume.

This material was removed at a production rate of approximately 70 cubic feet per man-hour or 2,800 ft.b.m. per man-day. Although the rate is low when compared to that obtained on normal logging operations, this method shows to advantage when compared to other two-stage operations where the main logging is followed by re-logging. Not only was a higher grade product recovered than on a similar area which was re-logged following the main logging, but a higher volume per acre was also recovered.

BRI Prefab Conference

With a research conference on "Preassembled Components" in modern building as one of its features, the Building Research Institute will hold its 1960 Fall Meeting, Nov. 15–17, at the Shoreham Hotel in Washington, D. C. Discussions will deal with the design and assembly of components for various categories of construction, including on-site and factory-prefab home building.

N. C. State College Has Kiln Drying Course

North Carolina State College will present its seventh annual kiln drying short course, Sept. 12–17 on the college campus. Featured in this year's program will be control of moisture content, drying without degrade, fast drying systems, and forced air drying.

The five and a half day course will be conducted by the College's School of Forestry, the U. S. Forest Products Laboratory, and the Southeastern Forest Experiment Station in cooperation with the college's Extension personnel and the Southern Furniture Manufacturers Association.

Instruction will cover all phases of drying and is aimed at conserving lumber, increasing kiln output, and obtaining moisture control. Included on the teaching staff will be Roy M. Carter and Al J. Stamm, both professors of wood technology, N. C. State College; Walton R. Smith, Rufus H. Page, and Louis I. Gabby, Southeastern Forest Experiment Station; Ray C. Rietz, kiln engineer, Forest Products Laboratory, Madison, Wis.; and representatives from Redman Engineering Service, High Point; Moore Dry Kiln Co., Jacksonville, Fla.; and Delmhorst Instrument Co., Boonton, N. J.

Delmhorst Co. Sponsors Research in Wood Physics

Dr. Eric A. Anderson, chairman of the Department of Wood Products Engineering at the New York State University College of Forestry in Syracuse, told that the Delmhorst Instrument Co. of Boonton, N.J. has sponsored a basic research project in the electrical properties of wood.

Recipient of the $500 summer research fellowship a Forestry College graduate student—Elvin T. Choong of Indonesia. Choong is a candidate for a Doctor of Philosophy degree in wood products engineering, specializing in wood physics. During his three-month exploration he has attempted to find out how to measure, by remote control, the moisture content of wood as it is being dried in a dry kiln.

Director of the 12-week, scientific study is Dr. Christen Skaar, associate professor of wood products engineering at the College of Forestry.

NAMES in the NEWS

Denman

Nelson

Two FPRS members were among the 4 new division vice presidents created by Southern Pine Lumber Company at the regular midsummer meeting of its Board of Directors, July 28, according to **Arthur Temple, Jr.,** president. The new officers are **Kenneth Nelson,** vice president for Land & Timber; **Joe Carter Denman,** vice president for Lumber Products; **Carroll Allen,** vice president for Fiber Products; and **Clyde Thompson,** vice president of the Forest Harvest Division.

Frank J. Hanrahan, executive vice president of the American Institute of Timber Construction, reports two additions to the AITC staff. **J. P. Thompson** has been named building code specialist, to work extensively with building code officials and similar groups, and **R. P. Wibbens** has joined as an engineering assistant to Mr. Hanrahan.

District managers for the Western Operations Department of the Borden Chemical Company have been announced by **R. T. Hanson,** geenral manager. They are **John Runkel,** who will be responsible for the sales and manufacturing activities of the company's products in Oregon, Southern Idaho and Wyoming; **F. W. Linehan,** who will handle sales and manufacturing in the Washington and Canada areas; and **B. B. Butler,** who is in charge of all sales and manufacturing in the California area.

William L. Keady, president and Fibreboard Paper Products Corporation, has resigned after 8 years as chief executive. He will continue as a Director and will be in charge of the company's foreign operations. **E. W. Carey,** vice president, marketing, has been elected president and chief executive officer. He has been with Fibreboard since 1957.

D. J. McCurry, of High Point, N. C., has been promoted to assistant to the sales manager–field of Bowater Board Company, it has been announced by **J. R. Hahn,** sales manager of the firm. Mr. McCurry will be engaged principally in field sales work with major hardboard users in areas not covered by company sales representatives.

A Minnesota and Ontario Paper company graduate research fellowship of $1500 has been awarded to **Richard C. Trochlil,** a 1959 graduate of the University of Minnesota School of Forestry. Announcement of the award was made jointly by **George Amidon,** woodlands director for the company, and **F. H. Kaufert,** director of the School of Forestry.

Herbert C. Sampert, industrial forester and executive, has been appointed lecturer and associate specialist in the University of California's School of Forestry at Berkeley, with responsibility for research forests.

EMPLOYMENT *Opportunities*

Positions Offered

E–401 Mid-West company is seeking a consultant organization or an individual or several individuals to take on a new product (folding doors) line. Desire a man to take the product from the detailed engineering drawing stage through the finished product. Will furnish him with detailed drawings and set up specifications. Present facilities at his disposal. Will also furnish an estimate of projected volume. (Sept.)

Employment Wanted

617—Engineer, Mechanical and Industrial, with wide experience in Woodworking and Finishing. Recent experience with particle board and polyester finishing seeks a managerial position (Sept.)

618—Quality Control or Product Development wanted by Wood Technologist with B.S. degree. Four years' experience in glued laminated timbers and four years' experience in plywood R. & D. Age 33, married, with 4 children. (Sept.)

619—Wood Technologist with 8 years' experience in research, production, and forest land evaluation in Southeast with company producing sewing machine cabinets. Desire like position with company with a future. B.S. in General Forestry and M.F. in Wood Technology. Prefer East and South. Age 38, married, one child. Resume on request. (Sept.)

620—Plant Superintendent—12 years' experience in production management and industrial engineering in furniture (case goods) and dimension plants. University graduate with B.S. in Wood Technology. Knows machines, all phases production, costs, incentives, layout, etc. Desire position as plant superintendent or equal. Age 34. Prefer Mid-South location. (Sept.)

POSITION OFFERED

State Agricultural Experiment Station has challenging opening for research man to direct progress in forest products investigations. New wood utilization research laboratory with excellent equipment and considerable latitude in developing broad program to find new uses for low quality wood. Ph.D. or M.S. with additional graduate training required. Request application form from Chairman, Department of Forestry, Ohio Agricultural Experiment Station, Wooster, Ohio.

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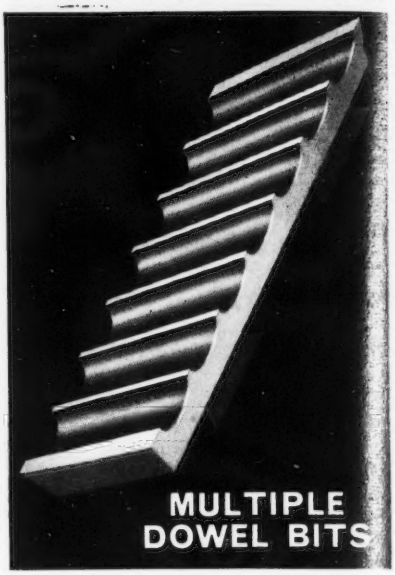

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FPRS FOREST PRODUCTS JOURNAL VOL. X, NO. 9 SEPTEMBER, 1960

FOREST PRODUCTS PAVILION at the Oregon Centennial, Portland. Photos courtesy of West Coast Lumbermen's Assoc.

Hyperbolic Paraboloids of Wood[1]

J. G. PIERSON and J. W. STORRS
Portland, Oregon

Forest Products Pavilion at the Oregon Centennial is a striking example of wood's ability to combine beauty with utility in imaginative modern design.

THE HYPERBOLIC PARABOLOID is a development of the strong tendency in recent years toward thin-shell and stressed-skin types of construction. The first bird to lay an egg understood the theory quite well, but it took people quite a number of years to learn how a thin shell could be made into a rigid structural member by merely building a stiffening curvature into it. For instance, a flat strip of 16 gauge steel, 9 inches wide and 10 feet long, will not be self-supporting standing on end. Rolled and secured into a 3-inch-diameter tube, however, it will support the weight of an automobile. The tube comes under the classification of singly curved surfaces, which also would include long-span barrel arches.

Domes, which were formerly constructed of heavy masonry blocks, are better constructed as thin-shell structures, like eggs, and would be classified as doubly curved surfaces. The advantage of the latter over the former is that it will resist deformation in any direction.

The hyperbolic paraboloid is similar to the dome in that it is doubly curved, but where the dome is completely convex, the hyperbolic paraboloid is convex on one axis and concave on the other.

The building described here is made up of a group of seven hyperbolic paraboloids. A dimensional description of one of them will illustrate their construction.

The plan dimension of each is 50 feet square. The supporting points are 8 feet above the floor, while the high points are 30 feet above the floor. The roof is made of two layers of 25/32 inch flooring. It is designed to carry a total load of approximately 85,000 pounds. Imagine, if you can, what the result would be if the roof had been 50 feet square, 1½ inches thick, supported at two corners, loaded to 85,000 pounds, and built flat. Of course the building has never had to sustain the design load—quite possibly it never will. Although it would be interesting to measure its deflection under such a load, it would not be a cause for concern. The double curvature built into the roof makes it impossible for it to deflect appreciably without changing the relative position of the boards in it to each other. There was considerable thought given to various methods to provide resistance to such relative movement.

[1] Presented at the Wood Industries Conference, Sept. 12, 1959, in Portland, Ore.

The Authors: James Pierson, a Portland engineer, developed the engineering aspects of the building in cooperation with John Storrs, Portland architect, who was the designer.

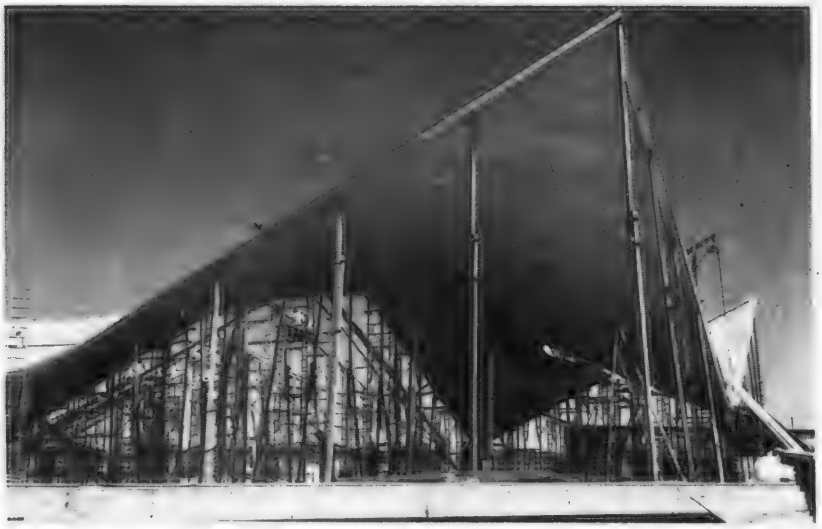

Fig. 1.—Second layer has been completed on the bottom surface, and the edge-stiffener has been nail-glued. Span of diaphragm is 70 feet; slope length on one side of paraboloid is 56 feet.

It would appear that most structures based on the hyperbolic paraboloid shape have been constructed in other countries than the United States, and that most of them have been constructed of reinforced concrete. This is because concrete is easily molded into warped shapes, and also because it is relatively simple to provide strength at points of high stress with the inclusion of reinforcing steel. This building has shown that it is comparatively simple to do the same job with wood. The method of analysis of stresses in the structure is the same for either concrete or wood, and, possibly, a mental picture of the manner in which the material works under the stresses is more easily formed by looking at the roof, or photos of it, than would be possible looking at concrete without the character of natural wood finish.

The edges of each roof are straight. If you were able to see along lines parallel to any of the edges, you would see that all lines paralleling edges in plan are straight. This means that forming the shape for construction with any material can be accomplished with straight lumber. Now, looking at the boards in the bottom layer of the roof (Fig. 1), it is seen that they are parallel to the diagonal axis of the roof through the supports. They form a series of parabolic arches which terminate at the edges of the roof at an angle of 45 degrees. The thrust of each arch at the edge can be broken into components, one acting perpendicular to and toward the edge, and one paralleling the edge toward the low corner of the roof.

Now, imagine the boards in the top layer of the roof, running parallel to the diagonal axis through the high corners. They form a series of parabolic suspensions that also terminate at the edges of the roof at an angle of 45 degrees and at 90 degrees to the direction of the arches. Each suspension exerts a pull at the edge that can be broken into components, one acting perpendicular and away from the edge and one paralleling the edge toward the low corner. When components of the arches and suspensions are combined, those acting toward and away from the edge neutralize each other, and those paralleling the edge toward the low corner add up to a thrust toward the support. The summation of the forces that contribute this thrust is determined by means of a mathematical equation which takes into consideration the size and unit load on the roof and also the rise or pitch. The last is quite important in that the thrust becomes much greater as the pitch is flattened.

Fig. 2.—Lower edge beam, designed to stiffen the diaphragm, is put in place. Success of the paraboloid depends on the connection of wood diaphragm to edge stiffener.

Transmission of Forces

After the thrust per foot along the edge is determined, the total accumulated thrust along the edge to the support is the force that must be transmitted by each edge-stiffening beam into the supporting buttresses. With the various forces involved in a tangible form, it is then possible to design each member as to size and connection to do its job, and then attempt to build it that way.

Let us be more specific as to actual forces involved in this particular building. The force transmitted by each layer of decking amounts to approximately 700 pounds per foot of edge, each layer acting at 45 degrees to the edge and at 90 degrees to each other. In order that all forces perpendicular to the edge be effectively neutralized, the two layers are secured to each other over the entire area by means of heavy, power-driven wire staples, and by gluing the two layers together in a four-foot-wide strip along all edges. The components of the forces of the two layers paralleling the edges combine to approximately 1000 pounds per lineal foot of edge, or a total of approximately 55 thousand pounds thrust along each edge into the supporting buttresses. The edge-stiffening members provided to carry this thrust consist of a 3-inch by 9-inch glued-laminated wood beam top and bottom of each edge. The bottom beams were shop-fabricated full size and length, and were shored into place to serve as edge templates for the deck. It was necessary to build quite a twist into the beams so they would conform with the varying slope of the decking.

Interior form joists, parallel to the sides, were supported on scaffolding at pre-determined elevations at 5-foot intervals. Glue was spread on the top surface of the bottom edge beam as the bottom layer of decking was

placed on it and nailed. With the bottom layer decking in place, the top layer was placed over it and secured with the wire staples. Glue was spread between the layers in the outer 4-foot strips, and the ends of the boards were nailed through the bottom layer into the bottom stiffening beam. With the decking all in place, the top stiffening beam was built onto the deck by gluing and nailing, a thickness at a time, four thicknesses of 1-inch by 10-inch boards. Extra thicknesses of 1-inch boards were added to the beams adjacent to the supports to provide additional stiffness where the maximum thrusts occur.

It should be noted that, in specifying the nailing requirements for the assembly, the nails at normal working stresses are adequate to transmit the thrust from the deck to the edge beams, but actually the nails only work to hold the boards together until the glue has set. The average maximum glue-line stress is computed to be less than 5 pounds per square inch. It is believed that, if the roof is completely dependent on nails for the transmission of the forces, there must be some deformation before the nails can begin to work, whereas deformation would be negligible to bring the glued joint to full stress. With the grain of the boards to be joined at 45 and 90 degree angles, however, it is imperative for the boards to be sufficiently dry that there will be no additional shrinkage. Otherwise, not much dependence can be put on the strength of the glued joint.

The edge-stiffening beams were erected and assembled with their lower ends in direct bearing into steel bearing shoes previously anchored and embedded in the concrete buttresses. The footings are so placed under the buttresses that the combined vertical loads imposed are at the center of the footings. The horizontal forces resulting from the thrust of each roof are resisted by tie rods embedded in concrete under the floor between the buttresses. Lag bolts through the bearing-shoe side plates into the edge-stiffening beams resist any lifting tendency that results from wind pressure under or negative pressure eddy currents over the roof. It was also necessary, with the open strip between the roofs, to provide the steel extensions at the interior high points of the roofs so they could be rigidly connected and thereby stabilize each other.

Fig. 4.—Applying first lamination of 1-by-6 Douglas-fir lumber. Note that purlins are straight lines and that the curve is achieved by laying the 1-by-6's from buttress to buttress, rather than by following the line of the supporting purlins.

The Next One Will be Easier

As might be expected, there were some things learned here, that could make another job like it easier or better constructed.

1. Be sure it doesn't rain. Gluing operations stop when the materials are wet.
2. Although the material cost will be somewhat higher, having the deck boards glue jointed into full length pieces will effect an actual saving by cutting labor costs, and will result in a stronger building.
3. Glue jointing the pieces of the top edge-stiffener beams into full lengths could give an improvement in strength.

There have been articles and pictures in print of other roofs of this type in various locations around the world, but none to the knowledge of the authors as large as these. Considerably larger roofs with the same pitch characteristics as these can be built of wood quite safely. If the pitch is flattened appreciably, the extremities of the roof will be more subject to deflection and vibration. If the pitch is steepened, the roof becomes more rigid, but the height might be excessive for most buildings. A single hyperbolic paraboloid roof with three corners supported at the same elevation and one free corner raised will make a stable roof that could be adaptable to quite a number of uses.

It was a most interesting and gratifying experience to be able to work out the engineering design for the project. Such opportunities occur very infrequently. It was definitely reassuring to see the contractor and his men take the ideas put on paper and turn out a finished product that actually exceeded expectations. And it was interesting to note the feeling of the craftsmen on the job. They likened it to working on a trampolene.

Fig. 3.—Peak connections were skeletons of four paraboloids lean against each other at this high point. The space between adjacent paraboloids is filled with corrugated plastic skylight.

PROTECTION FROM TERMITES:

Penta for Particle Board[1]

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Plastics Div., Monsanto Chemical Co. Seattle, Wash.

Sodium pentachlorophenate (1%) added to the resin before it is sprayed on chips should protect phenolic boards satisfactorily. Urea resin boards failed under extreme exposure conditions.

Fig. 1.—Left. urea resin (6%) board, ¾ inch thick, 0.75% penta, 1 year exposure Right: phenolic resin (4.5%) board, ¾ inch thick, 0.75% penta, 1 year exposure.

THE PARTICLE BOARD INDUSTRY, especially in the West, has shown a phenomenal rate of growth in the last few years. This growth, of course, is associated with a growing list of uses for the product. It was forseen that, if this new product could be made termite proof, it could well have unique advantages leading to substantial usage in termite-infested areas. In the tropics and semi-tropics, for example, the termite problem in regard to wood products has not had a completely satisfactory solution. Preservation of solid wood by impregnation of toxic material is time-consuming and costly in equipment and handling.

To get effective distribution of the chemical throughout the lumber, careful and exact steps must be followed. Excellent and thorough distribution of a toxic chemical in particle board, however, would involve only the addition of the toxic material to the furnish with no other increase in manufacturing costs. With thorough distribution of the toxic chemical in the product, satisfactory insect proofness should be effective as long as the chemical is present. One toxic material that has proven very satisfactory for lumber treatment and that also is quite insoluble is penta-chlorophenol. In addition, it was determined that this chemical in its salt form could be easily applied to the particle furnish along with the resin.

In the winter of 1956, Monsanto initiated a study with pentachlorophenol to determine how to best termite-proof particle board. Basically the investigation was designed to study the amount of pentachlorophenol needed for protection and the length of time that this protection was effective. First of all, boards were made in the laboratory to determine that pentachlorophenol was not detrimental to other board properties. When the boards were tested and shown to be satisfactory, other exposure tests were carried out. In late 1957, a mutual program was also initiated with Pacqua, Inc., Particle Board Division of Pacific Plywood Co., whereby commercial boards would be produced with pentachlorophenol incorporated, and then these boards would be subjected to extensive tests including the field test for determining termite and decay resistance of cellulose fiber materials. These exposure plots are maintained by Monsanto's Organic Chemicals Division at Pensacola, Florida, for the exclusive testing of termite activity.

Secondarily studied in the investigation were the methods of addition and effect of pentachlorophenol on process variables and such board properties as strength, color, and dimensional stability. Two chipboard binders, a urea and a phenolic resin, both in current commercial sales, were used as bonding agents in both the laboratory and the mill preparation.

To simplify this presentation, it will be in two parts. Part I will deal with the evaluation of the boards exposed to termite attack. Part II will deal with recommendations for use and general manufacturing conditions, and will discuss the retention of the pentachlorophenol in the board before and after exposure. An attached appendix gives standard conditions of manufacture, a description of the plots, and brief description of pentachlorophenol and one of its salts, sodium pentachlorophenate.

PART I

Laboratory Prepared Panels

Two sets of boards were prepared at the Monsanto Research Laboratory under standard conditions, with one set bonded with urea resin and one set with phenolic resin. Pentachlorophenol was incorporated into the board based on oven-dry particle weight at nominal levels of 0.0, 0.75, and 1.25 percent. Controls were tested in the laboratory, and the remainder of the board samples were installed in the Florida test plots for exposures of six months, one year, two years and three years. Two samples are evaluated and tested at each examination. To date, only the six-month and one-year exposures have been evaluated.

[1] Originally presented at the Winter Meeting of the Pacific Northwest Section, FPRS, Feb. 2, 1959, in Coos Bay, Ore. Revised and additional data included in May, 1960.

An examination of the urea resin onded boards for the six month exosure period from August, 1957 to ebruary, 1958, showed the boards be weaker in strength and somehat swollen compared to the conols. They exhibited some moderate gns of termite activity at the nominal 0 and 0.75 percent levels of pentalorophenol. Those boards with a minal 1.25 percent pentachlorohenol showed no signs of termite atk. This was a period of unusually ld weather for Florida, however, d this was thought to impair termite tivity; therefore, the six months exsure results may not be entirely presentative.

After one year of exposure, the rea-resin-bonded boards were noted to be excessively wet and swollen and had lost about 80 percent of their original strength. They were moderately to heavily attacked by termites. In addition to the termite attack, mold was observed on most of the specimens. Decrease of Modulus of Rupture was probably due to deteriotation of resin in the case of urea resins and not necessarily the result of decay. Conditions that normally promote infection with decay-causing organisms, high humidity, moisture, and so forth, also deteriorate urea resins. It is questionable as to what is causing the greatest damage, decay, termites, or urea-resin deterioration.

In Table I is listed a complete tabulation of the test samples after termite exposure of six months and one year. In this table, strength is reported as modulus of rupture, which indicates beam strength per unit of thickness. Since swelling has occurred, it follows that the actual breaking load has not declined quite so much as the indicated MOR, but neither would it be valid to calculate MOR for the actual breaking load and the original thickness.

The phenolic-resin bonded boards, as with the urea-resin boards, were exposed for the first six months during the unusually cold weather. The only sign of any termite attack at six months was very slight and confined to the board with no pentachlorophenol. The boards protected with ¾ and 1¼ percent of pentachlorophenol showed no signs of termite activity.

At one year exposure, the phenolic-resin boards were moist and moderately swollen, and when compared to the controls, the strength had decreased by about 50 percent. There was considerable termite damage to the ard samples that contained no pentalorophenol. As the pentachlorohenol concentration increased, the mite activity decreased, as the point ere the boards containing 1¼ per- of pentachlorophenol had negligible termite activity. (See Table I). It was also noted that there was no mold attack on any of the phenolic board samples.

TABLE I TERMITE EXPOSURE EVALUATION - SERIES I

LABORATORY PREPARED BOARD

Resin Binder	Nominal Pentachlorophenol	MOR and % Change			Thickness and % Change			Sp. Gr. and % Change			Termite Activity	
		0 Mo.	6 Mo.	12 Mo.	0 Mo.	6 Mo.	12 Mo.	0 Mo.	6 Mo.	12 Mo.	6 Mo.	12 Mo
Monsanto Urea Resin UF115	0%	2498	938 -63%	381 -85%	.752	.867 +15%	.952 +27%	.67	.62 -8%	.52 -22%	S-S-S O-O-S	S*-M*-S* M*-H-H
	.75%	1961	675 -66%	389 -80%	.781	.892 +14%	.940 +20%	.66	.58 -12%	.53 -20%	S-S-O O-S-O	H*-M-M* M-H-H
	1.25%	1708	707 -59%	464 -73%	.782	.886 +13%	.905 +16%	.66	.58 -12%	.56 -15%	O-O-O O-O-O	VS-S-M* S*-M-H
Monsanto Phenolic Resin PF575	0%	2316	1220 -47%	1020 -56%	.761	.846 -11%	.852 +12%	.66	.61 -8%	.55 -17%	S-S-S S-O-O	H-H-H H-H-H
	75%	1985	1117 -44%	988 -50%	.771	.882 +14%	.892 +16%	.66	.60 -9%	.58 -12%	O-O-O O-O-O	VS-O-O VS-VS-O
	1.25%	1690	1006 -41%	984 -42%	.794	.884 +11%	.890 +12%	.64	.59 -8%	.60 -6%	O-O-O O-O-O	O-O-O O-VS-O

Code letters referring to termite activity are positioned according to the six specimens of each experiment:

1	2	3
4	5	6

O = No termite attack
VS = Very slight
S = Slight
M = Moderate
H = Heavy
* = Moldy

On the basis of these tests it is apparent that the protection afforded by pentachlorophenol against termite attack is ineffective to preserve urea-resin-bonded boards through one year of *extreme exposure. It is also apparent the urea-formaldehyde-resin bonded boards were so swelled and weakened that the pentachlorophenol was no longer a determining factor in board deterioration.* All the phenolic-resin-bonded specimens with 0.75 to 1.25 percent pentachlorophenol content were preserved during the first year of exposure, while the untreated controls were badly damaged by termites. There was no mold attack of any type on any of the phenolic-bonded specimens, either with or without pentachlorophenol treatment.

To summarize the results obtained from the laboratory-prepared boards, it may be said that the preservation provided by pentachlorophenol in the phenolic-resin-bonded specimens was apparently not achieved in the urea-bonded specimens.

Of the untreated specimens, the termite attack appeared less severe on the urea-resin-bonded boards than on the phenolic-resin-bonded boards. The urea-resin-bonded boards were deteriorated, however and subsequent termite attack could be to a large degree obscured. In addition, to speculate: extreme moisture has been known to inhibit termite attack.

Commercially Produced Panels

To verify the results obtained with laboratory prepared panels, a second series of boards were made in the field with the co-operation of Pacqua, Inc., Particle Board Division of Pacific Plywood Company. These commercially manufactured boards were made in two groups: one group was bonded with urea resin and the other with phenolic resin. Sodium pentachlorophenate, the sodium salt form of pentachlorophenol, was incorporated into the urea-resin board based on the weight of oven-dried chips, at an intended nominal content of 0.0, 0.3, 0.65, and 1.0 percent. The pentachlorophenate was dissolved directly into the resin-size mix and was sprayed onto the chips with the resin. The board was then formed and pressed under standard conditions. Control specimens were retained and tested in the laboratory and the remainder of the board samples were installed in the Florida test plots for exposures of 4, 16, and 40 months. Six samples are evaluated at each examination. To date, only the 4-month and 16-month exposures have been evaluated.

The urea-resin boards, at the time of inspection at four months exposure, showed excessive wetness and swelling of all board specimens. With the boards containing 0.0 and 0.3 percent of pentachlorophenate, there were signs of slight termite attack. On those boards containing 0.65 and 1.0 percent pentachlorophenate, there was no sign of any termite activity after four months of exposure. At four months of exposure, however, the urea-resin-bonded boards all lost from 67 to 85 percent of their original strength. There was also a relatively large amount of thickness swell, and the specific gravity decreased over the original controls about 12 percent. At 16 months' exposure there was evidence of termite attack in all boards with the exception of the board containing a nominal 1.0 percent level of sodium pentachlorophenate.

The phenolic-resin boards, after four months of exposure, were slightly swollen and damp. Those boards that contained 1 percent of pentachlorophenate showed no sign of any termite activity. The board specimens that had no pentachlorophenate all showed

Fig. 2.—Urea resin (6%) boards, ¾ inch thick, no penta, 1 year exposure.

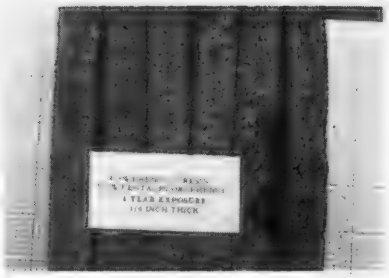

Fig. 3.—Phenolic resin (4.5%) boards, ¾ inch thick, no penta, 1 year exposure.

Fig. 4.—Urea resin (6%) boards, ¾ inc thick, 0.75% penta, 1 year exposure.

traces of termite activity that ranged from slight to heavy. It was noted that the strength stability of the phenolic boards was much greater than that of the urea-resin-bonded boards, and that the average decrease of strength over the original control was about 25 percent. Also, the change in specific gravity was half of that experienced with the urea-resin-bonded boards, the average decrease being about 6 percent; however, this is largely attributable to difference in bonding resins and not directly a result of termite damage.

After 16 months exposure there was termite attack in all boards. Apparently the nominal levels of sodium pentachlorophenate used are not high enough to achieve sufficient retention for protection.

To summarize all the results after 16 months of exposure of commercial board, all boards treated with sodium pentachlorophenate in excess of nominal application of 0.65 percent to bone-dry chips were effectively protected for a period of 4 months. At the 16-month evaluation all the boards, with the exception of the urea-bonded board with a 1.0 percent nominal application of sodium pentachlorophenate, showed evidence of some termite attack. However, termite attack on this urea board, if any, could easily be obscured by the loosening of the bond, and a general degraded appearance from lack of moisture resistance. Over all, the urea boards did not show as much *obvious* termite attack as did the phenolic boards; however, as mentioned above, they were grossly deteriorated, and subsequent termite attack could be to a large degree obscured.

Upon examining Tables 2, 3, and 4 (especially Table 2, columns 3, 4, 5, and 6), it seems apparent that a 1.0 percent nominal addition of sodium pentachlorophenate is not sufficient for effective termite protection. At a nominal 1.0 percent level an assay of about 0.5 percent of active pentachlorophenol is being achieved. With test interpretation and by a brief review of literature, this level is not believed sufficient to supply effective, long-lasting preservation. It is recommended that at least 0.75 and preferably 1.0 percent retention of active pentachlorophenol be attained for adequate protection.

To obtain additional data regarding retention of pentachlorophenol, a further experimental run was made at Pacqua, Inc,, in early April, 1960, at nominal application levels of 1.5 and 2 percent of sodium pentachlorophenate to the board. These boards are being assayed for their pentachlorophenol retention, and in addition will be added to the Florida plots. Until an evaluation is made of these boards, it is believed that the nominal sodium pentachlorophenate should be increased from 1.0 to 1.5 percent.

In conclusion, based on all tests to date, it appears safe to say that the phenolic boards protected by 1 percent *retention* of active pentachlorophenol will withstand a year of exposure under extreme conditions in contact with ground and would probably, in actual use under less extreme conditions, perform satisfactorily the function for which they were intended. Under the conditions of the severe exposure in *this* test, either phenolic board without pentachlorophenol - urea-resin board with any level of to[x]c can be considered unsatisfactory. In the case of the phenolic-resin-bond[ed] boards without penta, the failures due to termite damage. In urea-res[in]-bonded boards with or without pe[n]a failures are due to general deteri[o]ration by termite damage (possi[bly] through leaching and loss of pe[n]a chlorophenol), excessive swelli[ng], mold, and resin decomposition.

A logical question that may be ask[ed] concerns the use of untreated or pe[n]a chlorophenol-treated urea-resin boa[rd]s for interior purposes in tropical t[er]mite-infested areas. While it is kn[own] that urea resin is vulnerable to inordinately high humidities and temperatures in combination, it is not known how long, in terms of years, urea binder will withstand moderately severe conditions. It should also be understood that there are many different species of wood-attacking termites, and that these different species prefer varying habitats. Most species, however, especially the tropical varieties, prefer an environment in excess of 90 percent relative humidity and over 80°F. temperature. For this reason, a comprehensive, long-range study of termite resistance and durability of penta-

TABLE II TERMITE EXPOSURE EVALUATION- SERIES 2
COMMERCIALLY PRODUCED BOARDS

Resin	Panel Thickness Inches	% Sodium pentachlorophenate Nominal	% Pentachlorophenol Intended	% Pentachlorophenol Before Exposure Assay	% Pentachlorophenol 4 month Exposure	Termite Activity*** 4 months	Termite Activity*** 16 months	Controls vs. Exposed Specimen % Change in MOR 4 months	Controls vs. Exposed Specimen % Change in MOR 16 months	Controls vs. Exposed Specimen % Change in Density 4 months	Controls vs. Exposed Specimen % Change in Density 16 months
Monsanto Urea Resin UF115 at 6%	5/8	0	0	0	0	VS O O O O VS	S M M M VS-H	79%	90%	14%	34%
	5/8	0.5	0.25	0.19	0.11	O O O VS-O-O	S VS VS VS-O-O	67%	86%	11%	26%
	5/8	0.65	0.54	0.34	0.18	O-O-O O-O-O	O-M-S VS-O-O	-73%	-87%	-12%	23%
	5/8	1.00	0.83	0.49	0.39	O-O-O O-O-O	O-O-O O-O-O	-85%	-92%	-13%	-26%
Monsanto Phenolic Resin PF575 at 4.5%	3/4	0	0	0	0	S-VS-S VS-VS-S	H-H-H H-H-H	-38%	-23%	-6%	-8%
	3/4	1.00	0.84	0.5	0.38	O-O-O O-O-O	S-VS-VS M-M-S	-29%	-22%	-4%	-3%
	3/8	0	0	0	0	S-S-M H-H-H	H-H-H H-H-H	-40%	-58%**	-7%	-17%
	3/8	1.00	0.83	0.52	0.50	O-O-O O-O-O	S-VS-VS S-S-S	-32%	-47%	-8%	-8%

* Moldy
** Drop in density and strength due to physical loss of wood

*** O- No Termite Activity
VS- Very Slight
S- Slight
M- Medium
H- Heavy

g. 5.—Phenolic resin (4.5%) boards, ¾ inch thick, 0.75% penta, 1 year exposure.

Fig. 6.—Urea resin (6%) boards, ¾ inch thick, 1.25% penta, 1 year exposure.

Fig. 7.—Phenolic resin (4.5%) boards, ¾ inch thick, 1.25% penta, 1 year exposure.

hlorophenol-protected urea-resin and henolic-resin particle board under ypical use-conditions should be ndertaken.

PART II

Recommended Methods of Handling and Use of Pentachlorophenol in Particle Board Manufacture

Based on best knowledge to date gained from results from experimentation in the field and laboratory, the following techniques, recommendations and observations can be suggested on the use of pentachlorophenol in particle board.

For ease of handling and satisfactory solubility characteristics, it is suggested that sodium pentachlorophenate be used. This is a sufficiently water soluble sale (to 20 percent) of pentachlorophenol. Sodium pentachlorophenate is available in either powder, pellet, or briquet form. Generally, to date, in commercial production the pelleted form is used at 1 percent by weight of the bone-dry chips. Currently underway in research work are evaluations of various other concentrations. Technical sodium pentachlorophenate contains about 83 percent of active pentachlorophenol; for equivalency of active pentachlorophenol, slightly more should be used. From presently available data, however, the actual amount, within a few tenths of one percent, of included pentachlorophenol does not appear to be too sensitive. Until the completion of laboratory work, one percent by weight is being recommended. This is a usual amount of pentachlorophenol used in lumber poles and tie treating for termite and insect resistance.

The recommended method of adding pentachlorophenate to the chips is a technique developed at Monsanto whereby the desired amount of pentachlorophenate is dissolved directly in the resin and applied to the chips at the same time through the same sprays that the resin is applied. This assures a good distribution and facilitates ease of handling and usage. With a urea resin, because of its relatively neutral pH, it is desirable that, once the pentachlorophenate is added, the mixture be thoroughly agitated to insure rapid dissolving. One drawback of using pentachlorophenate with urea resin is that it raises the pH of the resin approximately 1 or 2 units. This in turn calls for longer press times to achieve satisfactory cure of the urea resin, and of course, the normal interrelation of flow, cure, and so forth of the resin is necessarily altered. It has been found necessary at times to increase press times approximately 23 to 30 percent when a urea resin is used.

Sodium pentachlorophenate, when used with phenolic chipboard resins, does not exhibit these drawbacks. Because of the original alkalinity of the phenolic resin, the pentachlorophenate dissolves very easily with a minimum amount of agitation, and does not greatly disturb the pH characteristics of the resin, so that there is no significant alteration of the resin system.

It should be mentioned that, in sustained production of preservative-treated particle board, it will undoubtedly be feasible to use the cheaper form of pentachlorophenol, penta, rather than the Sodium pentachlorophenate, by such devices as the pre-addition of caustic to the penta or the dissolving of finely divided penta into agitated resin.

There is an indication that rentention of preservative under exposure conditions is quite good for phenolic-bonded board, while urea-resin-bonded board has lost up to 47 percent by leaching (See Table 3). No explanation is obvious for the difference between intended penta percentage and assayed penta, although possibilities include imperfect input measurement, loss by vaporization, or improperly calibrated assay. Comparison of the assays on treated, unpressed furnish and pressed board indicate that little is lost in pressing, and that the discrepancy is between the amounts added and the amount assayed (see Table 4).

Both pentachlorophenol and sodium pentachlorophenate and also numerous other successful preservatives can be leached from the board if it is subjected to sufficiently severe and continued leaching conditions. It is assumed here that no major chemical bonding takes place. Even if the latter is the case, interest should be in how effective and lasting are the anticipated preservative properties, regardless of the leachability or retention. It is often the case that, under certain conditions, a preservative can be rendered entirely insoluble and at the same time ineffective. The practical answer will be provided in test plot sites at later evaluations. The pentachlorophenol is slightly volatile under normal pressing

TABLE I. ASSAYED PENTACHLOROPHENOL N BOARD

COMMERCIALLY PRODUCED BOARD

Thickness	Binder	Nominal Sodium Pentachlorophenate	ntended Net Pentachlorophenol	No Exposure Analysis	4 Month Exposure Analysis
5/8"	6% UF	0.0%	0.0%	0.0%	0.0%
		0.3	0.25	0.19	0.11
		0.65	0.54	0.34	0.18
		1.0	0.83	0.49	0.39
3/4"	4.5%PF	0.0	0.0	0.0	0.0
		1.0	0.83	0.5	0.38
3/8"	4.5%PF	0.0	0.0	0.0	0.0
		1.0	0.83	0.52	0.50

LABORATORY PREPARED BOARD

Thickness	Binder	Nominal Pentachlorophenol	ntended Net Pentachlorophenol	No Exposure Analysis	1 Year Exposure Analysis
3/4"	4.5%PF	1.25%	1.20%	0.87%	0.80%
		0.75	0.72	0.52	0.50
		0.0	0.0	0.0	0.0

conditions, and there is probably some loss. From our analysis of penta in unexposed boards, however, this does not appear to be significant. (See Table 3). There are indications that the penta concentration is very slightly lower around the edges of the board. This is conceivable since the penta is, to some extent, as mentioned, steam volatile.

Pentachlorophenol or pentachlorophenate, when used with phenolic resin, has been noted to impart a slightly reddish or purplish tinge to the board surface. Other board surface and appearance properties, including water absorption and dimensional stability, have not been noticably affected.

TABLE IV ANALYSIS OF PENTACHLOROPHENOL IN PARTICLE BOARD AND FURNISH BY NITRIC ACID OXIDATION

Pentachlorophenol Content Percent Based on Equilibrium Weight of Finished Board Conditioned at 75°F., 50% R. H.	Percent Intended Net Pentachlorophenol To Furnish	Pentachlorophenol Content Percent Based on Equilibrium Weight of Furnish Previous to Pressing. Furnish Conditioned at 75°F., 50% R. H.
0.20	0.25	0.18
0.18		
0.40	0.54	0.40
0.41		
0.67	0.83	0.57
0.62		

Appendix

Description of Exposure Procedure on Termite Plots: One hundred and eight specimens of particle board made in the laboratory were installed in the Pensacola, Florida, test plot in August, 1957; 144 specimens of commercially produced board were installed May 6, 1958. Specimens were cut 3 inches by 9 inches, and adjacent no-exposure controls were retained in the Seattle Laboratory.

The method of installation is to position two specimens on the ground with long edges parallel and in contact with the sod, tightly sandwiched between a pair of bricks. Another pair is placed against the otherside of one brick and so on to make a row one brick-length wide and one brick-width high. The ends are buttressed with extra bricks. Over this row are positioned more bricks laid flat to prevent direct rain weathering of the specimens.

Manufacturing Conditions of Laboratory Prepared Panels: The specimens were made with an intended nominal pentachlorophenol content of 0.0, 0.75, and 1.25 percent. These boards were made ¾ inch thick and at an intended specific gravity of 0.65. Urea resin was sprayed on agitated chips at 6 percent and petrolatum size at 0.5 percent. The phenolic resin was used likewise at 4.5 percent and the petrolatum size at 0.5 percent. The pentachlorophenol was dissolved in ethanol and separately applied at the intended percentages. The urea-resin-bonded board was pressed at 300°F. for 12 minutes, and the phenolic-bonded board was pressed at 350°F. for 12 minutes. Total moisture content into the press for both resins was 12 to 13 percent.

Manufacturing Conditions of Commercially Produced Boards: Pentachlorophenate was incorporated into both urea-resin and phenolic-bonded boards based on the weig of bone-dry chips at an intended no inal pentachlorophenate content of 0 0.3, 0.65, and 1.0 percent. Urea-res bonded boards were made at ⅝ i thickness and at a specific gravity 0.65. Urea resin was supplied at percent solids, and the wax emuls size was applied at 1 percent sol and was dispersed in the resin bef it was sprayed.

The phenolic-resin-bonded boa were made at ⅝ inch and ¾ i thickness and at an intended spec gravity of 0.65. The resin was appl at 5 percent solids, and 1 percent s emulsion was also dispersed in resin before it was sprayed. The pr temperature with the urea-resin-bon boards was 300°F., and with phenolic-resin-bonded boards w 340°F. The pentachlorophenol w used as sodium pentachlorophena and was dissolved directly into the resin at the time of resin application to the particles. "Nominal" means content of as-purchased toxic, which in the case of pentachlorophenate is 83 percent pentachlorophenol by assay.

DIELECTRIC HEATING AND

The Emerite Process[1]

S. H. W. BROOKS
Emerite Corp.
Jackson, Miss.

THE EMERITE PROCESS has undergone continuous research and development since 1948, and in January, 1959, the first commercial chemicals were sold. The Kroehler Manufacturing Co., Meridian, Miss. was the first plant to use Emerite chemicals, and manufactured a composition board known in the industry as "Cultured Wood". The Kroehler plant is now using all kiln dried and green wood waste, including all the sawdust and sanderdust.

The Emerite process was patented in England with British patent No. 761, 199 in 1954 and in the United States with patent No. 2,764,569. Other patents have been applied for.

Raw Material

When the composition board industry was in its infancy, basic sawmill waste was used. Through the years, sawmill waste has slowly been replaced by pulp logs peeler cores, and slabs for the manufacture of engineered flake in order to achieve greater strength and stability.

The Emerite process is a unique method of replacing the splinter, shaving, and flake board with an fiber board. Thus, it does away with the problem of selective particle si and species separation. By this proc any species of material can be utili in any basic form, with two lim tions: 1) the material must be lig cellulose; 2) the lignocellulose terial must be capable of being tur

[1] Presented at Session XV, Wood Composition Board (B), FPRS 14th National Meeting, June 5-9, 1960, in Montreal.

The Emerite process is semi-dependent on natural lignin as a binding agent, but fiber length, diameter, and type of felting also affect strength, stability. Dielectric heating makes this hardboard process economically sound.

PHYSICAL CHARACTERISTICS OF DIELECTRIC HEATING VERSUS CONTACT HEATING

24 hr. Soak at 70° F. (ASTM)

Thickness	Density	MOR, dielectric heating	MOR, contact heating	Dielectric, internal bond	Contact, internal bond	Dielectric, water absorp.	Contact, water absorp.	Dielectric, thick swell	Contact, thick swell
15/16"	40.8	1750	1250	125	100	15%	20%	5.5%	8%
1"	45.3	2125	1550	200	150	14.2%	18%	5.4%	8.5%
3/4"	49.0	2600	1850	250+	185	12.3%	15%	4.5%	7.5%
1/2"	35.0	1450	1000	75	30	18%	22%	3.5%	5.0%
1/4"	56.2	4210	3500	250+	200	10.5%	14%	2.5%	6%

Fiber used was mixed hardwoods, including 30 percent oak and 20 percent sawdust and sanderdust. Fiber generated from kiln dried and green waste.

into fiber. The quality of the fiber and quantity of chemicals used determines the end product desired.

Outstanding composition boards have been made from practically any lignocellulose type of material. The following lists a few of the types of materials tried with the Emerite chemical:

1. Aspen
2. All the oaks
3. All the gums
4. Bagasse
5. Cotton stalks
6. Corn stalks
7. Leaves and branches from various wood species
8. Bark mixed with wood
9. Douglas fir
10. Southern pine
11. White pine

A distinct advantage has been found in using sugar cane bagasse, including the pith, rather than depithed bagasse fiber. Also up to 40 percent of fines from any basic species can be used satisfactorily in making a standard low-density or high-density board. Past research indicates the fines tend to be more reactive due to their large surface area, and as the process is semi-dependent on the natural lignin in the particle as a binding agent, it has been found that the natural lignin can be freed more easily in the small fiber. The Emerite composition board however, still relies to a great extent upon the fiber length and diameter and type of felting for certain strength and stability characteristics.

Chemicals Used

There is nothing magic about this process. Actually, the fibers are glued together through a chemical reaction that utilizes the natural lignin in the wood. To achieve stability and semi-exterior qualities, a tempering oil is added. Under continuous heating at 300° up to six hours, depending upon thickness, it will polymerize and form a moisture-impervious bond around each fiber.

Dielectric Heating

Fundamentally, this heating procedure is quite simple. At present, a 40 by 20 inch single-opening press with a positive platen and a ground platen is used. The positive platen operates at a maximum voltage of 6000 volts and with a minimum of approximately 400 volts, depending on the thickness of boards desired. The platens are oil heated to a temperature of 350°. The primary reason for this is to give a good surface cure, and also prevent any of the steam from condensing on the platen surfaces and thus contaminate the board. Also a 10 percent increase in press cycle is obtained through the use of the heated platens.

A very good 1/8-inch hardboard can be produced by means of high frequency with a press cycle of 15 seconds, and correspondingly up to 1 5/8 inches in 4 minutes. The board does not have to be "breathed" as it normally would if the standard hot platen method were used. The basic board qualities have been greatly improved through the use of high-frequency curing.

Fundamental Concept of Dielectric Heating

Dielectric heating has been used in several European countries for several years. The author has no way of knowing how effective or ineffective this method has been. It is understood however, that when standard urea formaldehyde and phenolic resins are used to manufacture a particle board with high frequency, considerable arcing problems are encountered. The writer has been advised through reliable sources that various thicknesses are limited with conventional resins

Economic Study for 5' x 20' x 1 Opening Press
To Manufacture 3/4" Finishable to 5/8" Floor Underlayment

	50 Ton Per Day Cost per MSF 3 Shifts or 48 MSF	
RAW MATERIAL		
Wood @ $7.00 per ton (Bone Dry)	$ 8.75	
Emerite "A-x" @ 11¢ lb. solids	11.55	
Emerite "B-x" @ 10¢ lb. solids	12.50	
		$ 32.80
DIRECT LABOR		
(3 men - $2.00 per hr.)		
(1 man - $3.00 per hr.)	4.50	
		4.50
DIRECT MANUFACTURING COSTS		
Indirect Labor and Payroll Charges	2.18	
Repair and Maintenance Labor	1.01	
Repair and Maintenance Material	1.02	
Electrical Power @ 1¢ KWH (625 KWH)	3.12	
Fuel Oil @ 7¢ a gal. (110 Gal. per hr.)	3.85	
Operational Supplies	1.34	
*Finishing Costs Including labor, sandpaper and saws	10.39	
Samples and test specimens	.12	
Samples (cost of shipping)	.05	
*Warehousing and shipping	2.92	
Emerite royalty	.25	
General and Administrative including quality control	2.23	
		28.48
INDIRECT MANUFACTURING COSTS		
Property Taxes and General Insurance	1.50	
Depreciation for 10 yrs. ($150,000. per yr.)	10.40	
		11.90
Cost of sales are not included in this economic study		
GRAND TOTAL MANUFACTURING COSTS		$ 77.68

* - Arbitrary

The Author: S. Hunter W. Brooks graduated from Leatherhead Surry, England. After 6 years in military radar electronics, he majored in physics at the Univ. of Richmond, Va.

because of the arcing problem. With Emerite resin, a board as thin as 0.125 inch with a density of 50 pounds can be produced safely. The advantage of dielectric heating of poor thermal and electrical conductors is that it provides constant quantities of heat per unit volume when the material is homogeneous throughout, which is the direct opposite of contact heating. By this method, the temperature of the material can be raised uniformly within a very short period of time.

Difficulties Encountered With Contact Heating for Manufacturing Fiber Board

When fiber is used to manufacture a board, several problems occur. First and foremost is the natural insulating effect of a fiber. From experience it has been found that, to obtain the heat in the center of the fiber mat within the shortest time possible, a temperature of 430° is required on the platens of a hot platen press. The second-most important problem is a steam venting difficulty which occurs due to the natural denseness of a fiber mat. This can be through the use of a secondary drier just before the mat is felted. Also, the standard hardboard practice of breathing the press once during each press cycle has been adopted. It has also been found to be virtually impossible to make a 30 pound ½ inch board by conventional pressing methods. This is primarily due to the heat driving all the moisture to the center of the board and the board curing out before the moisture is all removed from the center of the board. This leaves a center line. The aforementioned difficulties have all been eliminated through the use of dielectric heating.

Four groups of information are presented in tabular form in this paper:

1. Physical characteristics of dielectric heating versus contact heating.
2. Actual economic cost study of a typical 50 to 80 ton per day plant.
3. Recapitulation costs of economic study.
4. Actual calculations showing power needed versus press cycle and weight of material.

The economic cost study of this plant will show that a break even point is reached on one shift a day with a production of 50 tons.

DIALECTRIC HEATING CALCULATIONS FOR A ONE OPENING 5′ x 20′ PRESS USING A 20 KW GENERATOR

Wo—Weight of bone dry wood
Wa—Weight of water in mat
DT—Temperature rise required
SpWo—Specific heat of bone dry wood—(.324)
SpWa—Specific heat of water—(1.00)
LV—Latent heat of vaporization—(970BTU)
(Energy needed to change one lb. of water to steam)

1. Wo × Sp Wo × DT—Sensible heat of wood.
   1 × .324 × (280° − 100°)—58 BTU per lb. of bone dry wood.
2. Wa × SpWa × DT—sensible heat of water. (Mat contains 3% moisture) 1 × 1.00 × (212°F. − 100°F.)—112 BTU per lb. of water.
3. Wa × LV—Energy needed to convert moisture to steam.
   1 × 970 BTU — 970 BTU per lb. water.
4. Total BTU required to heat wood—273 lbs. × 58 BTU — 15,834 BTU
5. Total BTU required to drive out moisture—8 lbs. × 1082—B,656 BTU
6. Total BTU required to cure board—24,400 BTU
7. In one minute there is available 11,400 BTU of power from a 200 KW generator.
8. One board can therefore be made in a little over 2 minutes.
9. An overall press cycle of 2 minutes and 30 seconds can be achieved.
10. This is equivalent to 24 boards in one hour or 2,400 sq. fet. of finished boards per hour.
11. Weight per sq. ft. 7.5 — 2.5 lbs.—One board has a total area of 109 sq. ft. out of press.
12. Therefore, there is required 6,000 lbs. per hour of untreated fiber or 72 tons of fiber a day is required to feed the press.
13. Because heated platens are also used, a 10 percent increase in capacity can be allowed, which would give us an 80 ton a day total through press capacity.

Recapitulation Costs of
Economic Study for 5′ x 20′ x 1 Opening Press
To Manufacture 3/4" Finishable to 5/8" Floor Underlayment

	50 Tons Per Day (Cost per MSF)			80 Tons Per day (Cost per MSF)		
MANUFACTURING COSTS	1 Shift or 16 MSF	2 Shifts or 32 MSF	3 Shifts or 48 MSF	1 Shift or 20.5 MSF	2 Shifts or 41.6MSF	3 Shifts or 62.4MSF
Raw Material	$ 32.80	$ 32.80	$ 32.80	$ 32.80	$ 32.80	$ 32.80
Direct Labor	4.50	4.50	4.50	3.75	3.75	3.75
Direct Manufacturing Costs	43.80	36.47	28.48	41.27	32.34	22.03
Indirect Manufacturing Costs	19.90	15.85	11.90	18.77	13.44	8.35
TOTAL MANUFACTURING COSTS	$ 101.00	$ 89.62	$ 77.68	$ 96.59	$ 83.23	$ 66.99

The cost of a plant designed to produce from 50 to 80 tons a day on a turn-key basis including buildings, foundations, equipment installed, and operating satisfactorily, would be approximately $1,500,000, depending upon the type of raw material used.

The Emerite Corp. feels it has an ideal plant design when the high-frequency press is used. The production capacity of this plant is as high as 80 tons of board per day. If kiln dried wood waste is used, it would not be necessary to have a wood yard and the plant could be operated by two men and one lead man.

One of the nicest features of this plant is that no caul trays are needed to transport the mats into the press. It is also believed that, through the use of a fiber and a good prepress, a mat can be made tight enough to be put into the press without the need of a moving belt through the press.

In summary, when a fiber-type intermediate density board is to be made most economical way to do so is with the use of dielectric heating. It has been felt in the industry for a long time that this was the correct approach, but up to now it has been impractical due to the use of standard resins and excessive moisture required for proper flow. Through the use of Emerite resin, however, which does not need excessive moisture for flow, a board can be manufactured well within economic limits.

Observe National Forest Products Week

October 16–22, 1960

Spraying Catalyzed Coatings[1]

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Chicago, Illinois

Catalyst is usually added either (1) in the pressure tank supplying the gun, (2) by a separate hose to the gun, or (3) between gun and surface to be finished with 2-headed gun. Current emphasis is on inhibited catalysts added by the manufacturer so that conventional spray guns can be used. Inhibitor is released when finish is sprayed or heated.

Fig. 1.—Two-headed gun for applying catalyzed coatings. Catalyst actually mixes with finish in the spray between gun and surface.

BEFORE DELVING INTO THE APPLICATION of catalyzed coatings, it might be well to comment briefly on the mechanism of drying of finishing materials in order to better understand the real value of catalyzed coatings. If, in Fig. 2, Position C represents a substrate such as a wood or composition board or metal surface, and a product such as a lacquer is applied to this surface at a wet film thickness corresponding to the distance between A and C without any evaporation of solvent from the lacquer at the time of application, then when this lacquer film dries by evaporation of solvent only, it will shrink down to Position B so that the dry film thickness will be approximately 20 percent of the wet film thickness.

In the true lacquer products, the only drying action that occurs is evaporation of solvent. The only real purpose of the solvent is to act as a carrier for the film-forming materials in the lacquer. To illustrate that the drying action is only solvent evaporation, all one needs to do is to wipe a lacquer film with a lacquer solvent that is used in the lacquer. It becomes quite apparent that the lacquer re-dissolves quickly and easily in the lacquer solvent.

[1] Presented at the North Central Regional Meeting of FPRS, Nov. 5, 1959, Chicago, Ill.

In the case of oil-type paints, such as house paints, and again referring to Fig. 2, with Position C being the surface to which the coating is applied and Position A being the total wet film thickness, the film dries first of all by evaporation of solvent and then by oxidation of the oil in the film. Oxygen is absorbed from the air and makes a chemical change in the film itself. The shrinkage during the drying process is radically less than that which occurs in lacquer, and in some cases the dry film will be perhaps 80 percent of the film thickness of the wet film.

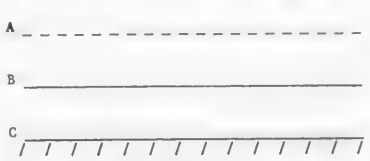

Fig. 2.—Schematic representation of drying. C represents surface to be finished, B is dry film surface, and A is surface of wet film.

In the case of conversion or catalyzed coatings, Fig. 2 can again be used to illustrate the drying mechanism, except in conversion coatings heat is normally used to cause a chemical reaction in the solvent-free film. Baking finishes used on automobiles and appliances, and for that matter, some of the baking finishes applied to hardboard used in the wood industry, are finishes that are converted chemically during this heating or baking operation. The film shrinkage from wet to dry film is, generally speaking, approximately 50 percent. The baked or cured or converted film is no longer soluble in the solvent originally used in the product, though it may suffer minor attack from such solvent. It will not re-dissolve or re-disperse in the original solvent.

In considering catalyzed coatings, a catalyst should first be defined as a material added to a paint-type product to increase the rate of reaction between two or more of the ingredients in the product, without any substantial change in the catalyst itself.

A few examples of catalyst might help to provide an understanding of how they work. Most persons have had some experience in applying house paint or barn or fence paint around homes, or of applying floor varnish or furniture varnish. Occasionally you find the product does not dry rapidly enough, or the instructions on the label of the container recommend the addition of japan drier or some other drier to the product to make it dry properly. In the case of oil-type house

paints or many so-called floor varnishes that use driers to increase the drying speed, the driers are true catalysts. They carry oxygen from the air at the paint-air interface into the paint film and speed up the oxidation process. In some cases they also speed up the reaction between the ingredients in the film. Thus, lead, manganese, cobalt, or japan-type driers used in house paint or floor varnish are true catalysts.

In industrial finishing with catalyzed coatings, it is possible to purchase products that can be mixed in small quantities, such as in a pressure tank with a catalyst supplied by the finishing material supplier. These products normally must be applied in a relatively short period of time. Otherwise, the catalyst will cause conversion of the product in the pressure tank. The length of time between catalyzation and the conversion in the tank is called pot life. If a product has a two-hour pot life, then in the paint application room it is necessary to mix not more than perhaps a 1.5 hour supply so that the equipment, including the pressure tank, hoses, and guns, can be cleaned before the product converts in the system. In the case of products catalyzed in pressure tanks and sprayed with conventional equipment, the system is normally called a *pressure tank catalyst system.*

Many paint spray equipment manufacturers have designed, developed, produced and are currently selling what are known as *catalyst spray guns.* An example of this type equipment is shown in Fig. 3. In this case, the finishing material to be applied is pumped or otherwise forced through one of the fluid hoses to the head of the gun. The catalyst is forced through the other hose into the head of the gun, and the two products are atomized simultaneously by air that comes in through the handle of the gun. It is necessary to control fluid flow rates in this type application so that the proper ratio exists between catalyst and paint.

Another method of introducing catalyst into a finishing system so that straight air drying can be used rather than baking is the so-called *two-headed gun* system. Fig. 1 illustrates one such gun. Other manufacturers have similar guns that accomplish the same basic operation. In this case, a resin or finishing material is filled into two separate fluid supply systems, either pressure tanks or circulating systems, and one catalyst is applied to one system and another catalyst or promoter is applied to the other system. Each of the systems is stable by itself, but when the two catalyzed materials are mixed, rapid conversion occurs. In the case of the spray gun of the type shown in Fig. 1, fluids are metered through these guns at approximately the same rate to each head of the gun. The atomized material mixes in the fan just ahead of the gun and melts in as a single film when applied to the surface to be coated. These materials then convert rapidly because of the additive action of the catalyst in one of the fluids and the catalyst or promoter in the other fluid.

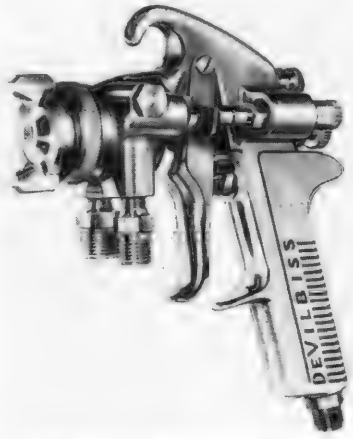

Fig. 3.—Typical catalyst spray gun.

The fourth system of applying catalyzed coatings is the one on which most companies are putting a lot of emphasis and a lot of hope for the future in air-dry coatings for the wood industry. This consists of adding the catalyst to the coating material at the manufacturer's plant in such a way that a pot life of many months is possible. A great many of the finishing materials used in industry today are catalyzed at the factory and applied with conventional spray equipment through the use of circulating systems or pressure tanks. This type of catalyzed coating is called *conventional spray equipment.*

The user of the material often does not even recognize or know, and for that matter, does not need to know that it is a catalyzed coating. Many of the baking synthetic finishes used on appliances today are baked at lower temperatures through the use of catalyst supplied in the paint manufacturer's plant than would be possible without the use of these catalysts. A typical example would be a product that would require 450°F. baking temperature for a period of 30 minutes to cause conversion without catalyst. But this same product, after catalyst addition at the manufacturer's plant, would bake in 20 or perhaps 30 minutes at 300°F. Similar things can be and are being done on coatings for force drying at temperatures as low as 120°F. or perhaps 130°F. for short periods of time.

In many of the conventional spray-system catalyzed coatings, chemists have found ways of adding inhibitors, or what might be called negative catalysts, to the coating material to prevent the reaction of the catalyst in the container. Some of these inhibitors are volatile materials that evaporate from the coating at the time of spray application or during the early period of air dry or force dry, thus permitting the catalyst to go to work and convert the coating.

What's Ahead

Now for a little "blue sky" thinking as to why catalyzed coatings are used and perhaps a prediction of what will happen in the industry.

The main reasons for using catalyzed coatings in the wood finishing industry are to provide greater solvent resistance or chemical resistance, to increase hardness of coatings applied to wood, without the use of elevated temperature or long bake times. There are limitations on force drying wood for any significant period of time at temperatures in excess of perhaps 130°F. or 140°F. Catalyzed coatings, however, offer the opportunity to the wood finisher to obtain the same type of chemical and solvent resistance, as well as abrasion resistance, hardness, and toughness as are possible on metal at the present time.

To use these catalyzed conversion coatings properly, however, often requires some changes in the manufacturing procedures or finishing procedures in order to obtain the maximum results from the coating. Patching procedures come up in almost every discussion of conversion or catalyzed finishes applied to wood because of the longstanding practice used in patching lacquers. This practice, in most cases, must be modified in order to repair damaged parts. In the metal finishing industry it is common practice for any significant repair spot to be refinished with an additional coat of the final coat formerly used in order to be sure that the repaired product has the same high quality of finish that was applied to the original product before damage and repair. In some cases, however, it is possible to repair conversion coatings without a complete application of the final coat over the previous final coat.

If we dream about the future of catalyzed coatings and consider the principles in the use of these coatings and the progress made in the last few years, it is conceivable that catalyzed, conventional-spray materials will be supplied so that people in the wood industry can capture the benefit of improved resistance properties, and tougher, harder finishing materials to provide increased uses for wood.

EVELOPING AN EXPERIMENTAL

Two-Piece Circular Saw Blade[1]

J. S. JOHNSTON

Ottawa Laboratory, Forest Products Laboratories of Canada, Ottawa, Ontario

A rim section carrying teeth is riveted to a center section so the rim can move radially in response to thermal strains. This temperature compensation reduces compressive stress under the teeth, increases saw stability.

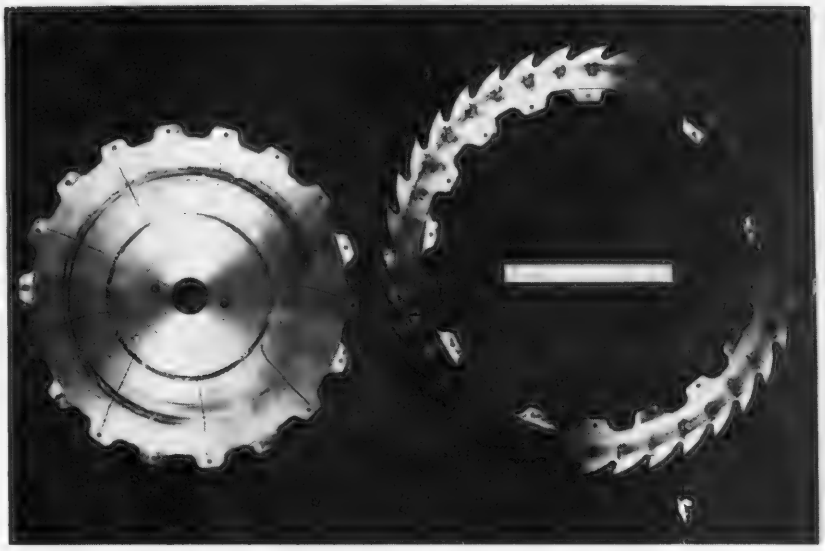

Fig. 1.—Rim and solid center section before assembly.

RESEARCH HAS BEEN CONDUCTED for a number of years in the specially equipped Research Sawmill at the Ottawa Laboratory, Forest Products Laboratories of Canada, on the many factors influencing the conversion of sawlogs into lumber. Generally, the aim has been to provide information for improved sawmill design and operation. Among the numerous studies made in this field have been investigations on the power requirements for circular head-rigs for sawing various species under different conditions of tooth shape, speed, and feed.

Recently, particular attention has been directed toward the effects of temperature and tooth-loading on the operation of circular saw blades. The objectives of this work were to improve the cutting accuracy and to reduce the kerf. Obviously, the development of a satisfactory blade thinner than today's circular saw blades would have many economic advantages. This paper outlines the first phase of development work accomplished in the design and testing of an experimental circular saw blade. It is hoped that this blade will lead to increased lumber recovery.

It became clear during preliminary work on a 48-inch saw blade that the stresses induced in the saw plate from the cutting forces were low, and that the main reason for not reducing plate thickness was the necessity to provide adequate lateral stiffness.

It is stated by Berolzheimer and Best (1)[3], that centrifugal force induces only tensile stress in a rotating disk, and that, therefore, the effect of such force is to stiffen the disk in a manner beneficial to its cutting action. It is further shown that the thermal gradient induced by the heat generated at the teeth of a circular saw blade causes high tangential compressive stress at the rim because of the restraint offered to free expansion of the heated rim by the cooler central portion.

Since the power applied to the saw blade is converted mainly to heat in the tooth area, it becomes necessary to accommodate the effect of such heating up to the temperature at which heat input and heat dissipation to the surrounding air are in equilibrium.

The common method of compensating for the adverse thermal compressive stresses induced in the saw rim is to insert compressive residual stress in the central section by hand hammering or rolling. The effect is to augment the tensile stress in the rim caused by centrifugal force and, therefore, to allow a greater thermal expansion of the rim before the compressive stress becomes high enough to cause buckling. Furthermore, it is extremely difficult to machine and heat treat a flat plate without distortion, and the hand hammering operation is also used to flatten the plate during its fabrication.

This local cold working of the saw plate leaves a highly complex state of residual stresses, however, some of which are so high that comparatively small additional stresses will cause permanent deformation by exceeding the yield strength of the material from which the plate is made. Additional stresses encountered in sawing may be from temperature gradients or from unusual mechanical loads. As pointed out by Barz (2), specification of the degrees of tensioning in common use are somewhat nebulous, the terms "loose", "a little loose", "tight", and so forth, being difficult to define. It would appear, therefore, that a method of temperature compensation more accurate than hand hammering would improve saw-blade action.

Examination of the stresses produced in circular saw blades by sawing indicated that if the rim of a

[1] Presented at Session VI, Wood Machining, FPRS 14th National Meeting, June 5–9, 1960, Montreal, Canada.

[2] The Forest Products Laboratories of Canada are a Division of the Forestry Branch, Department of Northern Affairs and National Resources.

[3] Numbers in parenthesis refer to the Literature Cited at the end of this paper.

The Author: J. S. Johnston holds a B.Sc. in mechanical engineering from Queens Univ., and has done post graduate work in stress analysis, electronics, and metallurgy.

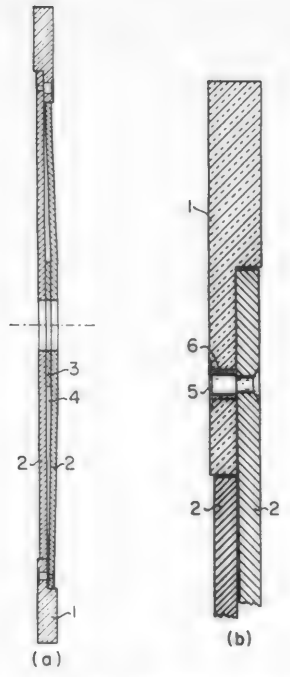

Fig. 2.—A, Full cross section view across diameter (not to scale). 1) rim cut from 30-inch saw blade; 2) 16 gauge steel sheet; 3) 24 gauge steel sheet; 4) space filled with epoxy resin. B, Enlarged view of riveted joint. 5) shouldered rivet; 6) clearance in hole for rivet.

saw blade could be mounted on the central disk in such a manner that it could expand freely with temperature increase, this cause of instability could be removed. In the past, several methods have been tried experimentally and some improvement has been noted. The radial slot method, which has often been used, does not offer sufficient freedom of rim expansion, and the benefits observed may result from saw cooling by increased air turbulence. Barz (3) describes several methods of connecting the rim section to the center section flexibly, including the use of spiral slots, which appear to provide adequate radial freedom. In all the aforementioned attempts with slots, however, the lateral stiffness of the blade was also seriously reduced.

The Experimental Blade

The method proposed in this paper is to join a rim section carrying the teeth to a center section by means of rivets, which by virtue of clearance in the rivet holes, allow freedom of radial movement to the rim.

Two 30-inch-diameter, 36-tooth, 10-gauge saws were obtained from a saw manufacturer.[1] One saw had been processed in the normal manner, while the other was processed from a blank without any heat treating or hammering in an effort to avoid residual stresses and to facilitate further machining. The first, or standard, blade, was used for comparison, and was not altered during the test except for the installation of gauges described later. The other blade, which will be termed "experimental", was cut, after some dimensional measurement, into two parts to form a ring and disk and rejoined as described below. After some observations, the center section of the experimental blade was then replaced by a laminated disk for the temperature and cutting tests.

Calculations showed that, if the temperature of a ring section of 2-inch radial width were raised by 100°F., the radial expansion at the mean radius of 13 inches would be 0.008 inch. Further, if this section were prevented from expanding, a tangential compressive strain on the order of 600 micro inches would be present. Accordingly, the experimental 30-inch blade was cut as shown in Fig. 1 so that lugs for rejoining would remain on each piece, the rivets to be at 11.5-inch radius. Each lug of the center and outside section was machined to half its thickness so that when assembled the total thickness would be the same as the original blade. Machining was done on alternate sides of the lugs to provide an interlocking joint. The blade was assembled with shouldered rivets as shown in Fig. 2b. It should be noted that one hole is concentric with the rivet and 0.010 inch larger than the rivet diameter so that the outer rim can expand diametrally 0.010 inch without restraint. Fig. 3 shows the assembled blade.

The Research Sawmill at the Ottawa Laboratory contains a standard circular headsaw with drive to the saw and carriage from individual D.C. electric motors which provide great flexibility in tooth velocity and feed speeds. Mercury slip rings on the saw shaft provide electrical connection from strain gauges and thermocouples on the rotating saw blade to suitable measuring instruments, so that measurements may be made during the normal sawing of wood.

The deviation from a plane normal to the axis of rotation (called lateral Total Indicated Run-out or T.I.R. and meaning peak-to-peak deviation) of the blades under test was measured at 13-inch radius by means of a dial indicator with each blade being rotated by hand. The standard

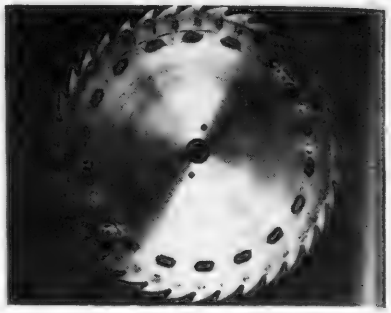

Fig. 3.—Two-piece experimental blade assembled.

blade showed 0.018 inch T.I.R. The experimental blade as received had a T.I.R. of 0.133 inch, but after it was cut and rejoined the T.I.R. was still high at 0.098 inch.

As might be expected, the experimental blade (with T.I.R. of 0.098 inch) when used to cut an 8-inch white pine cant was erratic in action and heated seriously in the center section from rubbing on the cut. An attempt was made to flatten the center section by hammering, and satisfactory saw operation in white pine was obtained. The T.I.R. at 5-inch radius was reduced to .060 inch. This left residual stresses, however, and since one objective of the test was to avoid these stresses induced by hand hammering, it was decided to make a new center section.

In constructing the new center section, two sheets of 16-gauge mild steel were sawn to shape as in Fig. 4 and a small 8-inch diameter disk of 24-gauge steel was inserted between the sheets during assembly to give a slightly tapered thickness. Final assembly was made on a glue press, with epoxy resin to bond the three parts. Thickness at the center was 0.150 inch by measurement, while that at the outside edge was 0.128 inch. This center section and the rim section of the experimental blade (Fig. 5) were then joined (in the same manner as before) by means of rivets with clearance holes. This resulted in a 30-inch saw blade with a thinner center section than on the first assembly (Fig. 3), constructed of lower-strength steel with no tensioning whatever. Fig. 2 shows the cross section. The lateral T.I.R. at 13-inch radius was 0.056 inch.

In view of the difficulty of using strain gauges on the saw while sawing, it was decided to mount only two on each blade, with each gauge aligned in the tangential direction and as close to the teeth as the saw guides would allow. Accordingly, the standard and experimental blades were fitted with one electrical re-

[1] The Simonds (Canada) Saw Co., Ltd., Montreal, supplied the blades required for the research work.

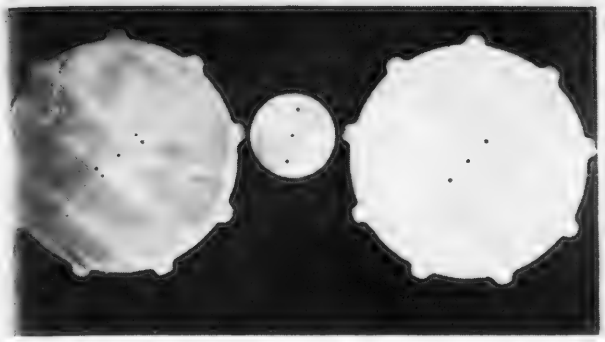

Fig. 4.—Parts for laminated center section of experimental blade.

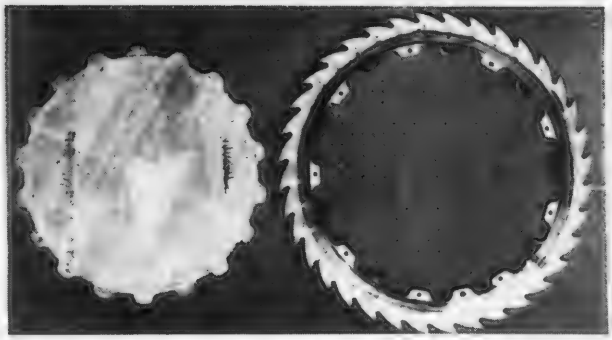

Fig. 5.—Original rim and laminated center section.

ıce type gauge on each side of the lade and directly opposite each ther at 12½ inch radius. A thermo- ıuple was soldered to the blade at the same radius. Epoxy resin was ısed to mount the strain gauges and also to cover the gauges and leads to protect them from abrasion during sawing. Since the strain gauges were inherently temperature compensated, the usual unstrained dummy gauge was not required to cancel the effect on gauges of unrestrained thermal expansion in the steel, and only active gauges were used on the rotating blade. The gauges were connected to the recording instrument in such a way that bending strains on the blade cancelled, and only axial strains were measured.

Fig. 6 shows the position of the strain gauges and thermocouple on the experimental blade, and Fig. 7 shows actual gauge installation in corresponding positions on the standard blade. Fig. 8 shows the experimental blade ready for sawing and the instrumentation used in this part of the test. To provide adequate clearance for the gauges, the swaged width of the teeth on each blade was increased to 0.250 inch. The experimental and standard blades were each mounted on the saw shaft and rotated at a speed of 1270 rpm. The tensile strain induced by centrifugal force at the gauge position was 100 micro inches per inch for the experimental blade and 20 micro inches for the standard blade; these values from actual measurement agreed with calculated values.

A temperature gradient was then induced by holding a piece of wood against the saw blade at 13½ inch radius. This caused, in about one minute, a temperature increase of 100°F. at the 12½ inch radius (thermocouple position). See Fig. 9. The resulting charred wood and tar-like deposits on the rim area contacted by the wood suggest the possibility of temperatures in excess of 560°F. (5). Since the maximum temperature measured by the thermocouple at a distance of one inch radially was 180°F., it is apparent that a high thermal gradient existed on the saw rim. The curves in Fig. 9 show strains during cooling with the saw blade still rotating. It should be noted that, in the experimental blade, the strain change induced thermally is tensile at the 12½ inch radius. This is an indirect indication that, in the higher temperature region at the 13½ inch radius, the strain must be in the compressive direction for equilibrium in the freely supported rim section. Thus the tensile strain induced by centrifugal force is increased by the thermal strain at the 12½ inch radius and reduced at the 13½ inch. At the highest temperature in Fig. 9, the centrifugally induced tensile strain immediately under the teeth has undoubtedly been reduced through zero and has become compressive.

In the standard blade, a compressive strain was induced at the 12½ inch radius by the thermal gradient, and this is indicative of a higher compressive strain just under the teeth where the temperature is higher (4).

As an example, the strain change induced at 160°F. in Fig. 9 is 100 micro inches tensile for the experimental blade and 250 micro inches compressive for the standard blade, both measured at the 12½ inch radius. If these are added to the centrifugally induced strains of 100 micro inches tensile and 20 micro inches tensile respectively, the resulting strain change is 200 micro inches tensile for the experimental blade and 230 micro inches compressive for the standard.

By the reasoning previously described, these figures imply a much higher compressive stress just under the teeth in the standard blade. The high compressive stresses in the standard blade are undesirable (produce buckling if sufficiently high), while tensile stresses are desirable and act in the opposite manner to stiffen a rotating disk. The noted instability above 140°F. (Fig. 9) at the thermocouple position on the standard blade is supporting evidence of the above. No instability was observed in the experimental blade.

Several boards ¾ by 8 inches by 12 feet long were cut from yellow birch cants with the experimental blade and confirmed preliminary findings that the stress from tooth loading was insignificant compared to temperature stresses. Blade speed was 1270 rpm.; feed speed was 60 feet per minute; maximum variation in board thickness was about 1/16 inch. During this sawing, temperature at the 12½ inch radius did not

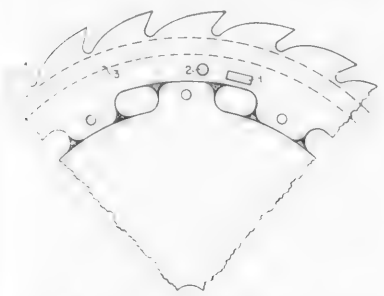

Fig. 6.—Segment of experimental blade ot to scale). 1) strain gauge; 2) thermople; 3) area of rim heated from rubg on wood.

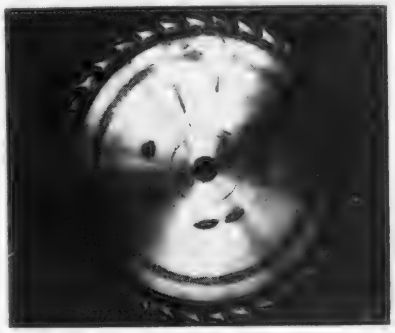

Fig. 7.—Standard saw blade, showing one strain gauge and thermocouple (other strain gauge on opposite side).

Fig. 8.—Circular headsaw showing instrumentation and experimental blade ready for sawing.

exceed 100°F. Then the blade was deliberately heated by friction from holding a piece of wood at the 13½ inch radius, and cuts were made before it cooled. This was done at 20°F. increments from 80°F. to 180°F., and no decrease in sawing quality was observed. The highest temperature at which a test cut was made, measured at the 12½ inch radius, started at 180° and had dropped to 160° at the end of the 12 foot length of cut. Strain dropped from 150 micro inches tensile to 50.

The experimental and standard blades were each used without instrumentation to cut about 700 board feet of lodgepole pine from logs about 10 inches in diameter and 12 to 16 feet long. Blade speed was 1270 rpm, and feed speed was 110 feet per minute. Sawing quality was about the same, that is approximately 1/16 inch variation in board thickness. In other respects also, the performance of the two saws was similar.

The experimental saw blade was not subjected to further operating conditions because of intended changes in design. It is proposed to modify this design by (a) improving the method of joining the rim to the center section, possibly by use of spring clips instead of rivets, (b) reducing the radial width of the rim to allow a larger center section and to further reduce the thermal gradient, and (c) to further increase the ratio of rigidity to weight in the center section.

An investigation of vibration characteristics with suitable instrumentation will be important in assessing the value of new designs.

It appears from the work accomplished to date that it will be possible to reduce the saw blade thickness as a result of increased stability in the presence of thermal gradients. The resulting reduction in kerf would provide definite economic advantages by reducing the volume of sawdust and consequently increasing lumber recovery.

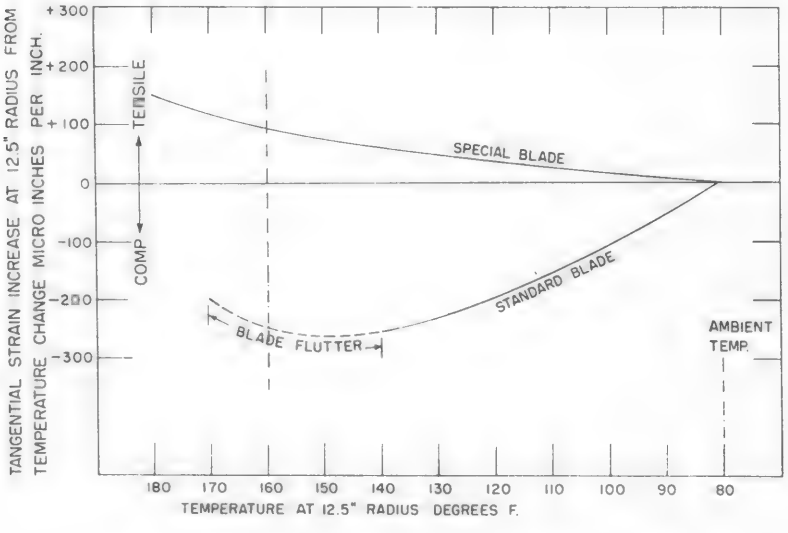

Fig. 9.—Relation between strain and temperature during cooling of experimental and standard blade.

Summary

1. The function of tensioning circular saw blades is to compensate for thermal expansion of the rim.

2. If the rim is joined to the center section so that free expansion is possible, the blade will saw satisfactorily with a flat central section containing no residual stresses.

3. The material from which the central part of a blade is fabricated need not be of high strength.

4. Sawing accuracy is dependent on the flatness of the blade while sawing.

5. The higher tangential tensile stress in the rim of the experimental two-piece blade from centrifugal forces is of advantage in stiffening the blade.

This is believed to be the first attempt to use a blade with a separate rim for temperature compensation, and further work with this design concept will be undertaken.

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FUNDAMENTAL ASPECTS OF THE

Wood Cutting Process[1]

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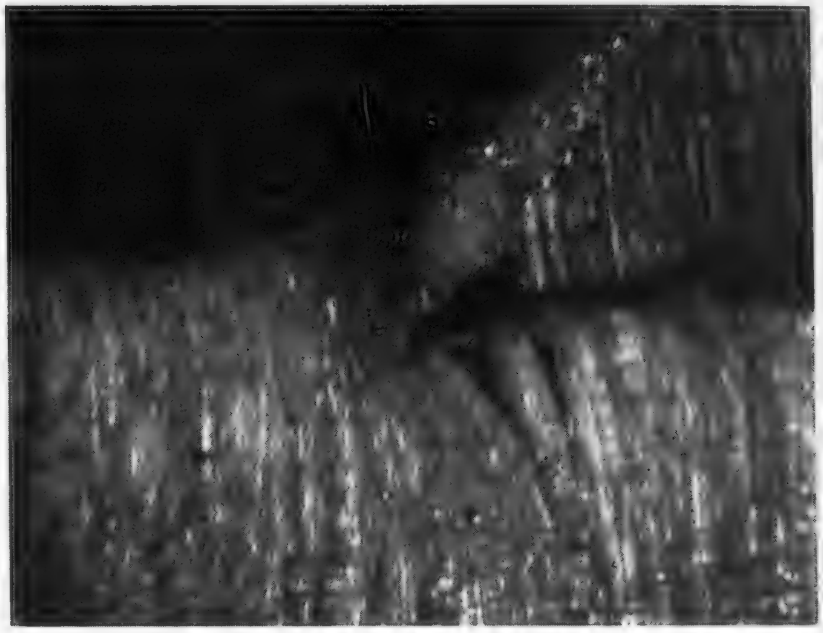
Action of a cutting edge on wood was studied to find basic concepts common to all machining processes. Types of failure related to surface quality and cutting efficiency can be predicted by a formula based on an analytical cutting model.



Typical splits along the grain below the cutting plane.

A BROAD VIEW of the field of wood machining reveals at first sight a host of problems associated with a wide variety of machining processes. These have usually been considered in piece-meal fashion, in the belief that each machining process has its individual problems. This remains true, but in order to economize research efforts and expense, it seems logical to develop, as far as possible, a fundamental approach that deals with basic concepts common to all processes, and this was the primary object of the work to be described.

If, with this aim, the question is asked "What is the central problem of machining wood in particular?", it is found that many wood machining problems are not peculiar to wood, but fall in the categories of machine design, metallurgy, kinematics, and so on. Such a classification isolates what is considered to be the hard core of wood machining problems generally, concerning the situations where a single cutter, of variable shape, takes a variable path through a work-piece at a variable speed and at variable angle to the grain. The wood itself is of course subject to many variations—the more important being variations of mechanical properties with species and moisture content. Further, this cutting process can be regarded as a sequence of separate actions, as was noted by Reineke (1),[2] and these may be distinguished as (a) chip severance, and (b) chip break up and removal.

Phase (a) is the essential action of a cutting edge on wood, while (b) is concerned with movement of the severed chips. The latter phase will have considerable variation in emphasis and treatment in the many types of cutting processes, whereas the severance phase is common to all such processes and is therefore of greatest general importance, especially since it involves a high proportion of the energy consumed. Since the shape of any cutting edge, however complex, can be resolved into a number of straight segments, straight edges can be used in analysis and experiments in the expectation that the results can be synthesized for the more complex cases. The problem in this form has been attacked by many workers under the assumption that it is necessary to consider cutting speed as an influential variable. But work with normal cutting speeds is very difficult and expensive, so that an important question bearing on effective research is whether it is necessary to study cutting at these speeds, or whether results observed at conveniently low speeds can apply also to high speeds. It was therefore considered necessary to investigate this matter before proceeding further.

The Effect of Cutting Speed on Cutting Forces

Work on the effect of cutting speed is well reviewed by Lubkin (2), and it is evident that some results show practically no effect on cutting power, while others show a curve with a minimum at some speed, or a decrease with increasing velocity.

Even workers such as Voskresenski (3), who believes that speed has a negligible effect on forces, state that surface quality improves at higher speeds—Walker (4) calls it "cutting sweeter". This common belief may be

[1] First-place winner, 1960 Wood Award competition. Also presented at Session VI, Wood Machining, FPRS 14th National Meeting, June 1960, in Montreal.

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[2] Numbers in parentheses refer to the Literature Cited at the end of this paper.

attributed to the fact that, in practice, a higher cutting speed is almost always accompanied by the cutting of a thinner chip, so that the cutting forces and surface damage are both reduced.

The essential question is whether cutting speed affects the physical and mechanical properties of the wood. Therefore, the evidence of Liska (5) on the effect of strain rate on wood properties is of interest. He found that strength in compression parallel to the grain and in flexure increased 8 percent for every 10-fold increase in testing speed up to 24 inches per minute. If these results could legitimately be extrapolated so far, it could be concluded that wood should be many times stronger at normal cutting speeds, and that cutting forces should increase correspondingly.

It is to be noted that most experiments have covered less than a six-fold increase in cutting velocity, so that at most an increase of 6.5 percent in cutting forces or power should have been observed, and this could have been masked by experimental error in some cases.

As pointed out by Koch (6), another factor that tends to increase tool forces as cutting velocity increases is the energy required to change the momentum of the chips, but his computation shows that this would contribute no more than about five percent of the tool forces at 10,000 fpm. Other factors suggested as contributing to an increase in cutting force are "chip compression (7)", and "dynamic support" (8) which may be references to a viscous or Maxwell effect, (9) which increases with velocity. Such an effect would also explain the results of Liska discussed above.

The initial decrease in cutting forces with increase of velocity is ascribed by Thunell to reduced friction on the grounds that, in many materials, friction coefficient decreases with increasing sliding speed. Another factor that might cause cutting forces to decrease with velocity is increase in temperature, which results from a tendency toward adiabatic conditions (9). It is known (10) that strength decreases one-half to one-third percent per degree F. increase in temperature. If a temperature of 150 degrees F. existed, and this is quite possible according to the work of Reichel (11) on tool temperatures, the resulting loss of strength would be about 40 percent, which would roughly balance the increase in strength due to high straining rate mentioned above.

Hence, on lines suggested by Freudenthal (9) for metals, a possible explanation for the variation in results from the several studies of cutting speed is that there are counter influences, an increase in cutting forces due to increased straining rate (Maxwell effect) being opposed by decreases due to the higher temperature, and possibly by reduced friction. This is illustrated in Fig. 1. The shape of the cutting force curve would depend on the variation of the three interacting effects with velocity, and according to the conditions of the experiment could approximate a horizontal line or a curve of varying shape. Apart from the uncertainties discussed above, however, there is a region of uncertainty at the very low end of the scale of cutting velocity, since Franz (12) has observed that, as static conditions were approached, alteration of the cutting process took place, which often resulted in changes of chip type. Only Kivimaa (13) reports a direct comparison of forces in this region, and his apparatus is dynamically suspect (14). This indicates a hazard involved in developing a theory of chip formation based on static considerations, and shows a need for further investigation in this region of cutting velocity.

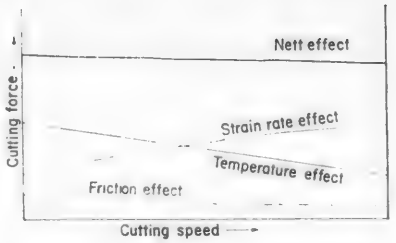


Fig. 1.—Suggested interaction of various effects in cutting wood.

Criticisms that apply to most of the machining experiments reported are, firstly, that they deal with a percussive action, so that results could be affected by dynamic properties of the system of wood, tool, machine, and measuring device. Secondly, no evidence of statistical analysis is given in any of the articles. A third possibility in some cases is that wattmeter recordings of motor input may not have been adjusted for motor efficiency at various speeds. It would be necessary to meet all these criticisms before one would be justified in drawing anything but a horizontal straight line through a plot of cutting forces against speed.

It appeared that many of the difficulties concerning machine and dynamometer might be avoided by using a continuous type of cutting such as that of a lathe, thus reducing the effects of impact.

Investigation of the Effect of Cutting Speed by Means of a Lathe: Continuous cutting conditions were obtained at speeds varying from 2,700 to 27,500 fpm by cutting on the edge of a wood disk mounted on a high-speed lathe. Cutting and feed speeds were recorded by electronic counters. The cutter and dynamometer were as described by Franz (12). The dynamometer, which had a natural frequency of 1500 c.p.s., was connected through a multi-channel DC amplifier to a dual-beam oscilloscope, the X-sweep of which was triggered by a contact on the lathe nose-plate. The superimposed traces from up to 10 successive revolutions were photographed with a Polaroid camera. The work-piece was a laminated disk of 3 inch diameter from which a rim of yellow poplar 0.25 inch wide was formed ahead of the cutter by an auxiliary cutter. Cuts at low speeds of 0.5 and 24 inches per minute were made on a milling machine (13) on pieces from the same disk as cut on the lathe. Cutting angle was 10 degrees, and nominal chip thickness was 0.010 inch. A typical photograph for 8,000 rpm (23,300 to 27,200 fpm) is shown in Fig. 2. The amplitude of the force oscillation in each half-revolution due to grain direction changes was somewhat attenuated at the highest speeds, so that median values were taken and plotted as shown in Fig. 3, against their regression line represented by the equation $P_x = 13.5 + V \times 9.23 \times 10^{-5}$ (1) in which P_x is the parrallel cutting force (pounds) and V is the cutting speed (fpm).

Despite the smallness of the regression coefficient, it was significantly different ($P = 0.05$) from zero. It proved possible to explain this in terms of the energy required to reduce the speed of the chips by using the equation

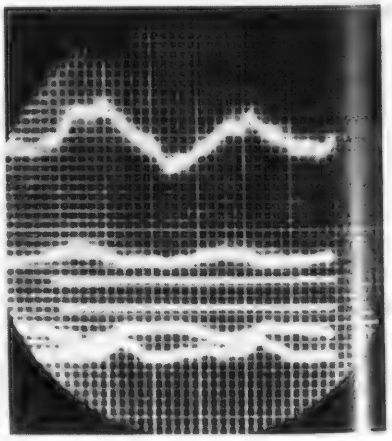


Fig. 2.—Photo of oscilloscope, showing about 130 traces of forces in cutting at 23,300 to 27,550 ft. per min. in dry yellow poplar. Upper wavy line = parallel force of 1 pound per line; bottom wavy line = normal force of 1 pound per line. (outward thrust) Note additional traces made after feed was stopped.

$$\delta P_x = \frac{btdV^2}{2g} \qquad (2)$$

where

δP_x = increase in parallel force, pounds.
b = width of work-piece, inches.
t = nominal chip thickness, inches.
d = density of wood, lb. per cu. ft.
V = cutting speed, ft. per sec.
g = gravity constant, ft. per sec.^{2}

For the measured density of the wood used, this equation gave an increase of 1.5 lb. for a cutting speed increase of 28,000 fpm, as against 2.6 lb. from the regression line. This difference was not statistically significant, and hence the slope of the regression line may be attributed to chip deceleration.

It was not possible to compare surfaces remaining after cutting for the full range of speeds, since the hydraulic feed could not be reversed instantaneously and the final surface was formed by very light cuts. However, another lathe with mechanical feed that could be stopped suddenly was used to form surfaces at 1120 fpm, and these surfaces were indistinguishable from surfaces formed at 0.5 in. per min. In addition, study of movie film taken at 0.5 and 21 in. per min. and the flash photographs taken by Chardin (15) of saw teeth cutting at speeds of 3,600 to 10,000 ft. per min. showed very similar modes of chip formation.

Despite the restricted cutting conditions, these results are regarded as conclusive, for there do not appear to be reasons other than chip acceleration why the effect of cutting speed should be different at other cutting angles, species, and moisture contents. The theoretical implication is that the essential cutting process remains unchanged over this tremendous (300,000-fold) range of cutting speeds. To reconcile this result with those of Liska (5), it is necessary to postulate that his relation would not fit results at testing rates much higher than he used, and that the true relation is not logarithmic but asymptotic to a certain maximum value, which occurs at some strain rate below that reached in cutting at 0.5 in. per min. with 10° cutting angle. Further, if the suggestion represented by Fig. 1 is valid, these results imply that, in this range, the effect of cutting speed on friction is negligible, and that the strain rate and temperature effects are exactly opposed, as might be expected if adiabatic conditions were reached at some cutting speed below 0.5 in. per min.

This leaves some doubt as to what strength values to assume in an analysis of the cutting process, but it seems probable that the values at the strain rates involved in cutting would not be much higher than the maximum obtained by Liska.

In any case, it may be concluded that the results from experiments at cutting speeds as low as 0.5 in. per min. can be readily applied to cutting at and above normal working speeds.

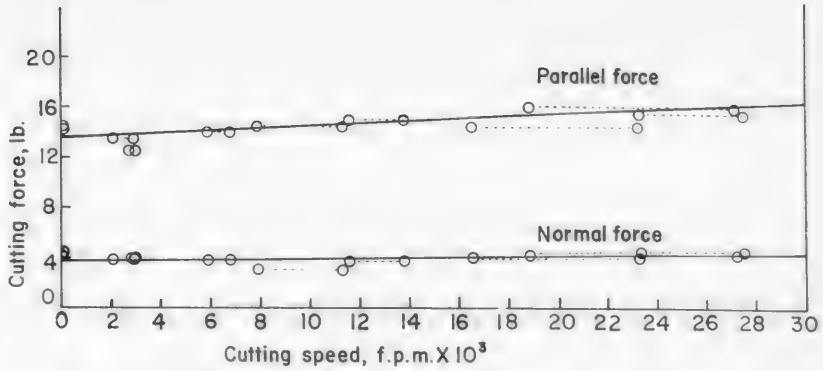


Fig. 3.—The effect of cutting speed on forces. Yellow-poplar, 0.25 inch wide, cutting angle 10°, nominal chip thickness 0.010 inch.

Orthogonal Cutting

The most basic cutting situation is one much used in metal-cutting research (9), and applied to wood-cutting research by Franz (12). In orthogonal cutting the cutter has a straight edge wider than the work-piece and perpendicular to the velocity vector, which moves with uniform velocity in a plane parallel to the surface of the work-piece (see Fig. 4). The situation thus becomes a plane problem of mechanics, with quasi-equilibrium assumed. The success of Franz (12) in developing an analysis to fit his experimental results, based on properties obtained from standard tests, involved an important advance from the analytical point of view.

It might be expected that such a fundamental cutting situation for wood might have aspects in common with that of other materials, especially those of cellular type, and this appears to be so, as discussed later. In attempting a general analysis of cutting action in wood, however, a seemingly insuperable obstacle is the extreme anisotropy of the material. Here the limit of generality is reached, and attention must be directed to certain limited ranges of cutting directions with respect to the grain.

By far the most important cutting actions are those typified by planing, rip sawing, and rotary veneering. The corresponding orthogonal cutting situation can be specified by the angles made respectively by the cutting edge and cutting velocity vector with the grain direction of the wood. Thus the typical planing action is 90°–0°, the typical rip-sawing action is 90°–90° and the typical rotary veneering action is 0°–90°. It is felt that an analysis developed for each of these situations could be readily extended to some extent on each side to account for variations that occur in practice, but they

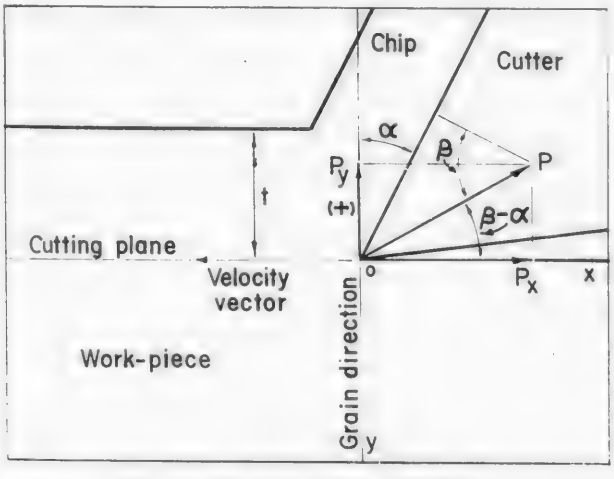


Fig. 4.—Orthogonal cutting at 90°–90°.

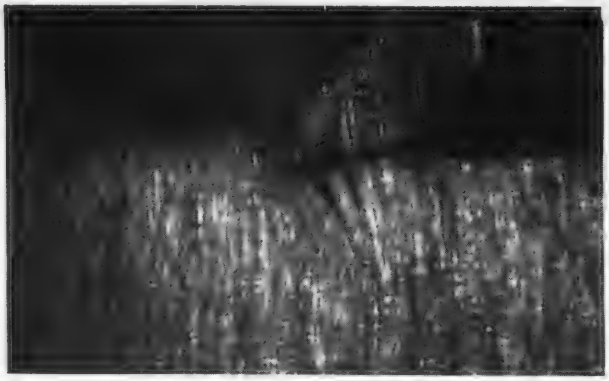


Fig. 5a.—Type I(a) failure in saturated eastern white pine (*Pinus strobus*). Cutting angle 40 deg., nominal chip thickness 0.010 in.; X 30.

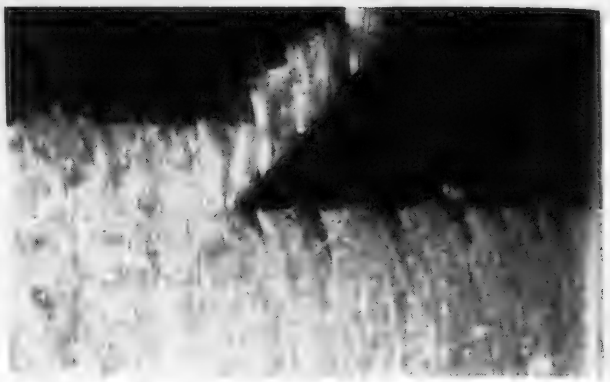


Fig. 5b.—Type I(b) failure in eastern white pine (*Pinus strobus*) at 5 percent moisture content. Cutting angle 45 deg., nominal chip thickness 0.030 in.; X 30.

are so distinct that it appears very difficult to provide a single analysis covering two of them, although this would be desirable for some machining processes such as turning.

For investigational purposes, attention was focussed on the 90°–90° cutting situation, because of its importance in sawing, and because there were no reports of slow-speed studies in this area.

Preliminary Observations of the 90°–90° Cutting Situation: The general 90°–90° cutting situation is sketched in Fig. 4. To define the problem to be analyzed more clearly, some preliminary observations were made of orthogonal cutting at 0.5 in. per min. with the equipment described earlier in connection with slow-speed cutting studies. A stereo microscope was used to view the cutting at up to 60 magnifications through plate glass bolted to the wood specimen, with the cutter carefully ground on the end to form a good corner against the glass. This prevented the fibers from being pushed outward and resulted in a more realistic view of the deformations in the vicinity of the cutting edge. Still and movie photographs were taken to record the various failure modes, and rough cutting force values were obtained.

The most important variables involved were considered to be species properties, moisture content, cutting angle (α, Fig. 4) and chip thickness (t). The species used in this preliminary study covered a wide density range, and included eastern white pine (*Pinus strobus*), yellow-poplar (*Liriodendron tulipifera*), sugar maple (*Acer saccharum*) and common persimmon (*Diospyros virginiana*). They were cut while saturated and at 5 percent moisture content, with cutting angles of 5, 30, and 40 degrees, and nominal chip thicknesses of 0.005, 0.010 and 0.030 in.

Failure Types: At cutting angles below about 20 degrees, cutting was too irregular to be classified; deflections were great and wood was removed by scraping or crumbling. Since low cutting angles do not occur except in a minor way in cutting at 90°–90°, these irregular failure types were not given further attention.

Study of the photographs showed, for the higher cutting angles, a definite sequence of failure types. As might be expected from the grain direction, there is a tendency for failure to occur below the cutting plane due to stresses transmitted across this plane. Failures above and below the cutting plane are intimately related, even in the first cut, where the original surface is prepared by cutting with a smaller nominal chip thickness. Four types of failure were recognized within the regular sequence, but it was found convenient for analytical and practical purposes to consider only two major types with two sub-types in each. These are described below.

Type I Failure (Repetitive) Fig. 5. The distinguishing feature of this type is that, after the first cut, the average cutting forces are essentially the same for successive cuts. Splits occur along the grain below the cutting plane. In Type I(a) these may be short and regular (Fig. 5a), associated with small wave-length and amplitude of the recorded cutting forces and comparatively high surface quality. In Type I(b), (Fig. 5b), two, three, or sometimes more short splits may occur between fairly regularly spaced longer splits that detract from the surface quality. In both cases, after the first cut, the spacing and length of the split remain essentially the same, which accounts for the regularity of the average cutting forces in successive cuts.

Above the cutting plane, each subchip is formed by shear along the grain simultaneously as a split forms below. In cuts after the first, the subchips are loosely linked continuously in Type I(a), but in Type I(b) they are in groups corresponding to the spacing of the major splits.

Type II Failure (Cyclic) Fig. 6. This failure type is associated with a cyclic variation of average cutting forces with successive cuts. Failures occur in a plane perpendicular to the grain and parallel to the cutting plane, at a variable distance below it. They may be intermittent (Type II(a), Fig. 6a) or continuous (Type II(b), Fig. 6b). In Type II(a) this failure is accompanied by severance at the cutting plane and shear above forming subchips so that the broken end of the lamina remains in place to be removed by the next one or two cuts. In Type II(b) (Fig. 6b) severance occurs continuously at the cutting plane. The chip above the cutting plane may be sheared into sub-chips or remain intact so that two practically continuous chips are formed, one above and one below the cutting plane (Fig. 6b).

In both types, depending on the continuity and distance below the cutting plane of the failure, various types of cyclic variation occur in the average cutting forces in successive cuts. For instance, there may be no contact with wood in one or two successive passes of the cutter after the first, then a gradual return to a condition similar to that of the first cut after which the cycle repeats itself. Both of these failure types result in a very poor surface, and low cutting efficiency.

Summary of Effects: All of the variables chosen were influential, and the various effects will now be discussed in terms of the failure types described, for the higher cutting angles.

With increasing species density, the failure tended to vary from Type I

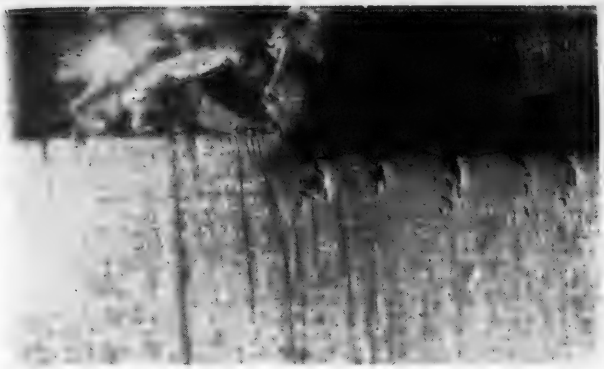


Fig. 6a.—Type II(a) failure in eastern white pine *(Pinus strobus)* at 5 ercent moisture content. Cutting angle 30 deg., nominal chip thickness .030 in.; X 10.

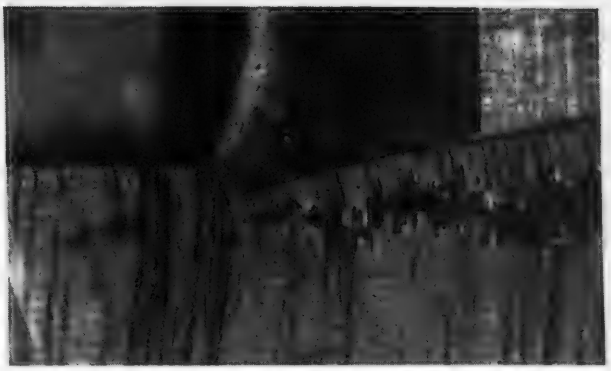
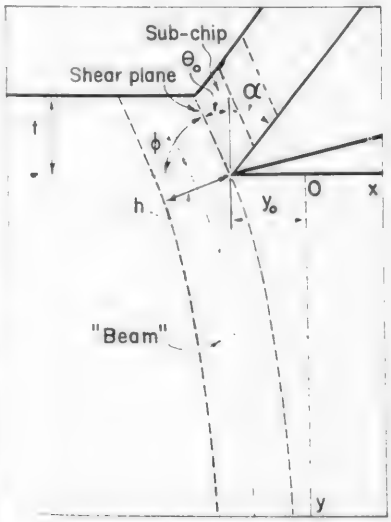


Fig. 6b.—Type II(b) failure in common persimmon *(Diospyros virginiana)* at 5 percent moisture content. Cutting angle 30 deg., nominal chip thickness 0.030 in.; X 10.

(a) through type II(b) and cutting forces increased.

Moisture content had a great effect. In saturated wood the predominant failure type was I(a) with slight splitting, and low steady cutting forces. This was in marked contrast to cutting at 5 percent moisture content, for which failures below the cutting plane were always deeper than the normal chip thickness, and the predominant failure type was type II. Cutting forces were high and the normal force, especially, showed oscillation.

At the cutting angles below about 20 degrees, irregular types of failure developed. At very high angles, failure tended to either Type I or Type II (b), depending on moisture content and density. Severance at the cutting edge produced a continuous chip in either case. Cutting force increased and the normal force on the cutter changed from negative (into the work) to positive (away from the work) with decreasing cutting angle.



7.—Model for cutting at 90°–90°; mi-infinite beam on elastic foundation.

With increasing chip thickness, the usual trend appeared to be from Type I(a) through II(a) for all saturated woods, and low to medium-density species, and from a crumbling action to Type II(b) in dense species.

This brief study of observed effects served as a guide to what was required of an analytical model on which to base predictions concerning the effects of the various factors, when cutting in or near the 90°–90° cutting situation. Since Type I failure was associated with a better finished surface and more efficient cutting, it was considered that the principal purpose of an analytical model should be to aid in predicting the probable occurrence of the two failure types, with the associated maximum forces, for a given set of cutting conditions and wood properties.

Analysis for the 90°–90° Cutting Situation

The problem as defined is essentially that of a rigid wedge indenting an orthotropic half-plane. After a vain search for a reasonably exact analysis for this problem, it was necessary to resort to less exact methods to develop a useful model. Since failure is not confined to the boundaries of the potential sub-chip, and stresses must be considered for an indefinite zone of wood, it appeared that the concept of a beam on an elastic foundation might provide a suitable model, especially since the basic theory for this concept was well developed and collated by Hetenyi (16). Since in this theory properties of the material of the beam are considered separately from those of the foundation, this could be used to account partially for the difference in mechanical properties of wood parallel and perpendicular to the grain, respectively. It was recently found that Voskresenski (3) developed an analysis on these lines before 1955, but his work is open to criticisms that will be referred to later.

Fig. 7 illustrates the model base on the concept of a semi-infinite beam, the lower end of which is embedded in a foundation whose depth (in the x-direction) is large compared with that of the beam. If the depth of the beam is not assumed or derived from the observed thickness of the laminae, the concept becomes abstract since the isolation of the beam is imaginary and requires that shear between the imagined beam and its base be ignored. By treating the depth of the beam as unknown, it was hoped to derive the thickness of the laminae when formed.

It may be seen that there are two concepts involved in the model:

1). The potential sub-chip is regarded as being held in quasi-equilibrium between the steadily advancing cutter face and the top face of the beam. The sub-chip is assumed to be formed by shear failure parallel to the grain in a shear plane forming the interface between the sub-chip and the beam (see Fig. 7) at an angle to the cutting direction (x-axis).

2). The forces required to cause shear failure also deflect the imaginary beam, and the slope (O) at the cutting plane ($x = o$) is the complement of the shear angle, so that both concepts are involved simultaneously at the shear plane. Then the failures below the cutting plane are related to the behavior of the beam and foundation under the action of the cutting forces.

Initially, in the present work, it was assumed that the cutting forces reached a maximum associated with the maximum shear stress on the shear plane at the moment of sub-chip separation, and that the deflection produced below the cutting plane would correspond to these forces. On this assumption, it appeared possible to obtain the cutting force from a criterion for failure in shear above the cutting plane, and decide which of the two failure types is more probable from

the bending stresses in the model beam at instant of failure above the cutting plane.

Criterion for Failure at the Shear Plane to Form a Sub-Chip: Since a shear failure is assumed for the range of cutting conditions discussed above, relations for equilibrium of the chip developed by Merchant (17) for metal cutting can be applied to wood, by using the shear strength parallel to the grain. It must be acknowledged that some of his assumptions may not apply as accurately to wood as to metal. In particular, distribution of normal stress on the shear plane is ignored, it being assumed that failure is not by tension perpendicular to the grain.

Merchant's analysis gives for the parallel cutting force P_x

$$P_x = \frac{\tau_o \, bt \cos(\beta - \alpha)}{\sin\phi \cos(\phi + \beta - \alpha)} \quad (3)$$

where

τ_o = shear stress at failure, psi
β = friction angle = arc tan μ
α = cutting angle
ϕ = angle between the shear plane and the x axis
b = width of work-piece
t = nominal chip thickness.

The normal cutting force (P_y) is related to P_x by

$$P_y = P_x \tan(\beta - \alpha). \quad (4)$$

By means of values of ϕ from measurements made on photographs, and friction values from various sources (12) (7), cutting forces were computed from equations (3) and (4). These are presented in Table 1 for comparison with values observed in cutting tests, and the associated failure type.

Beam on Elastic Foundation: It would have been preferable to consider the cutting force as a load distributed over a distance equal to the nominal chip thickness at the end of the semi-infinite beam, but the equation involved could not readily be solved for a general situation. Therefore the cutting force P_x was considered as concentrated at the end of the beam, the deflection curve of which is given by

$$x = \frac{2 P_x e^{-\lambda x}}{k} \cos \lambda x. \quad (5)$$

At the load point (x = 0) the deflection is

$$x_o = \frac{2 P_x \lambda}{k}, \quad (6)$$

and the beam slope (Θ) at this point is

$$\Theta_o = \frac{2 P_x \lambda^2}{k}. \quad (7)$$

Here k is the foundation modulus

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Table . . Comparison of Observed Cutting Forces with Values Computed from Equations (3) and (4)
Width of Workpiece 0.25 In. Nominal Chip Thickness 0.030 in.

Species		Moisture Content	Cutting Angle, Deg.	Parallel force, lb. Calc.	Parallel force, lb. Observ.	Normal force, lb. Calc.	Normal force, lb. Observ.	Failure type
Eastern white pine (Pinus strobus)	*	Sat.	40	14	20	-3.2	-2.5	I(a)
		5%	"	23	34	-5.3	-6.5	I(b)-II(a)
Yellow-poplar (Liriodendron tulipifera)	*	Sat.	"	17	24	-3.9	-1.8	I(a)
		5%	"	31	33	-7.2	-7.0	II(a)
Sugar maple (Acer saccharum)	*	Sat.	"	36	40	-8.4	-6.[illegible]	I(a)
		5%	"	60	100	-13.9	-5.0	II
Sugar pine (Pinus lambertiana)	+	Sat.	40	11	18	-1.0	-3.8	I(a)
		4%	30	25	39	-4.8	-5.0	I(a)
		"	40	23	28	-6.3	-7.3	I(b)
Yellow birch (Betula alleghaniensis)	+	Sat.	30	15	44	-1.1	-4.7	I(a)
		"	40	14	30	-3.7	-6.7	I(a)
		4%	30	60	89	-4.2	-10.0	I(b
		"	40	44	76	-11.4	-19	I

* Mechanical properties used were mean values for species

\+ Mechanical properties used were obtained from matched material

given by Biot (18) for an isotropic elastic solid, put in the form

$$k = 0.65 \frac{b E'}{h} \left(\frac{E'}{E}\right)^{\frac{1}{3}} \quad (8)$$

where

b = width of beam and foundation,
h = height of the beam
E′ = modulus of elasticity of the foundation in compression
E = modulus of elasticity of the beam in bending

The parameter λ is given by

$$\lambda = 4\sqrt{\frac{k}{4EI}} = \frac{1.18}{h}\left(\frac{E'}{E}\right)^{\frac{1}{3}} \quad (9)$$

where I = the moment of inertia of the beam cross section. Voskresenski (3) used equations similar to (3), (6) and (7) together with the assumption that the foundation failed in tension simultaneously with the shear failure above the cutting plane, to solve for P_x, x, h, and Θ_o. He assumed a simple Winkler (16) type of foundation, however, which cannot be considered indefinite in depth. Also, for a semi-infinite beam Θ_o is very sensitive to load distribution and the values for a concentrated load are much higher than those observed, resulting in low values for P_x. Since a convenient expression was not available, a simultaneous solution involving Θ_o was not attempted, and the failures above and below the cutting plane were considered separately.

Insertion of the Biot expression (8) for k in (4), gives, for $y = 0$

$$x_o = \frac{3.63 P_x}{E' b} \quad (9)$$

The beam depth h is not involved in this expression, and the simple model breaks down at this point. To find h it is necessary to assume a relation between x_o and h. The simplest relation is $x_o = h$, which is to assume that once fiber severance begins the recovery is very rapid, and is complete before the cutter advances further. As a result, equation (9) gives

$$h = \frac{3.63 P_x}{E' b}. \quad (10)$$

On the basis of observed values of P_x, h was calculated for the species and cutting conditions given in Table 1, and good correspondence with observed values was noted. Since h does not appear directly in the following analysis, however, and has little significance in itself, these data are not presented.

The bending moment for M for the beam is given (16) by

$$M = \frac{-P_x e^{-\lambda x} \sin \lambda x}{\lambda} \quad (11)$$

and is at a maximum where its derivitive is zero, or

$$e^{-\lambda x}(\cos \lambda x - \sin \lambda x) = 0$$

which gives

$$\lambda x = \frac{\pi}{4}.$$

Hence the maximum bending moment (M_{max}) is

$$M_{max} = \frac{-P e^{-\frac{\pi}{4}}}{\lambda} \sin \frac{\pi}{4}$$

Applying the elementary bending equation, and substituting for λ and P_x from (9) and (10) respectively the maximum bending stress $\sigma_{y\,m}$ is given by

Table 2 Comparison of Maximum Bending Stresses Given by Equation (1.) with Modulus of Rupture in Bending

Cutting angle 30-40°; nominal chip thickness 0.030 in.

Species		Moisture content	Theoretical bending stress, psi	Modulus of rupture psi	Ratio Col. 3 / Col. 4 percent	Failure type *
Eastern white pine (Pinus strobus)	+	Sat.	4,050	4,900	83	I(a)
		5%	8,900	8,600	103	I(b)-II(a)
Yellow-poplar (Liriodendron tulipifera)	+	Sat.	4,860	6,000	81	I(a)
		5%	11,500	10,000	115	II(a)
Sugar maple (Acer saccharum)	‡	Sat.	6,000	9,500	64	I(a)
		5%	19,000	15,800	120	II
Sugar pine (Pinus lambertiana)	‡	Sat.	3,800	5,300	72	I(a)
		4%	10,000	11,600	86	I(b)
Yellow birch (Betula alleghaniensis)	+	Sat.	4,450	6,900	65	I(b)
		4%	20,700	21,500	96	I(b)

*Constant over a range of cutting angles from 30 to 40 deg. and a range of nominal chip thickness from 0.010 to 0.030 in.
+Species-average values of elastic moduli were used
‡Elastic moduli obtained from tests on matched material

$$\sigma_{y\,max} = 0.45\,E'\left(\frac{E'}{E}\right)^{-\frac{1}{3}}. \qquad (12)$$

It may be seen that, as a result of the assumption in equation (10), $\sigma_{y\,max}$ depends only on the elastic constants and is not dependent, as might be expected, on cutting angle and chip thickness. In choosing the relation $h = y_0$ the bending stresses in the beam have been fixed and thus apply strictly only to certain combinations of conditions.

Observations confirmed, however, that the failure type was in fact independent of cutting angle and chip thickness over a wide range. Hence it was possible as in Table 2 to compare maximum bending stress values computed from equation (12) with modulus of rupture, for a range of cutting angles from 20 to 40 degrees and a range of chip thickness from 0.010 to 0.30 inch in which the failure type was essentially constant. The accord of the results shown attest to the validity of equation (12).

Attempts to account for the occurrence of the laminae and the length of the split between them, by postulating failure in tension perpendicular to the grain, were unsuccessful and the equations derived are not given.

Discussion of the Analytical Results: It is evident from Table 1 that the theoretical values for cutting forces vary in accord with the observed values, but are generally lower. This discrepancy is less for the saturated and low-density woods, where the failure type is I(a). In these cases it is possible that the available friction values were too low, or that a higher shear strength value should be applied due to the velocity effect discussed earlier. In the case of the dry, higher density woods, however, the discrepancy is greater than could be reasonably explained in this way. It should be noted that Type II failure predominated in these cases, and it was concluded that an explanation lay in the failure mechanism associated with this failure type, as discussed later.

If equation (12) is considered as a criterion for the incidence of Type II failure, Table 2 shows that in each case where the maximum bending stress is below the modulus of rupture, failure is of Type I, and where the stress exceeds the modulus of rupture, Type II failure occurs. Where the two values are close, as in the case of eastern white pine, both failure types may occur in different parts of a cut. This was observed to apply over a range of cutting angles from 30 to 40 degrees and a range of nominal chip thicknesses from 0.010 to 0.030 inch. At a chip thickness below 0.010 inch, Type II failure is less likely and above 0.050 inch it is more likely.

Equation (12) implies that failure type depends principally on the ratio of the elastic moduli respectively perpendicular and parallel to the grain. The available data (10) show that this ratio is highly dependent on moisture content, which accounts for the contrast between failure types for saturated and dry wood. Further, it was observed that a moisture content of 15 percent was sufficient to change failure in eastern white pine, yellow-poplar, and sugar maple from Type II to Type I. Evidence will be presented later, however, to show that blunting and friction may also have some influence.

For the normal range of cutting conditions, equation (12) is regarded as a satisfactory criterion for predicting surface quality where this is an important consideration, and for indicating the likelihood of an inefficient cutting action. It follows that considerable control over surface quality and cutting efficiency can be exercised by varying moisture content.

To obtain a more detailed analysis relating failure type to chip thickness and cutting angle, it is necessary to know more concerning the relationship between the deflection and severance phases of indentation. This would eliminate the assumption concerning the ratio of y_0 to h involved in equation (10), and would permit a more general relationship to be developed.

The Identification Stage of Cutting

It is evident that the indentation stage of cutting plays a key role, and this will now be discussed in detail, on the basis of intensive microscopic observation.

At first contact of the cutter with a virgin work-piece the wood at the cutter edge is deflected without rupture. This deflection stage has usually been ignored on the assumption that a work-sharp cutting edge produces a stress intensity much in excess of the strength of the material. But observation has shown that this stage is negligible only with very sharp cutters and high rake angles. Otherwise, wood deflection becomes considerable before fiber severance commences. The surface into whch the edge is indenting becomes convex on either side, and especially below the cutting plane is highly stressed in tension parallel to the grain. This stress may reach such a level before severance commences that failure occurs in tension parallel to the grain, and results in Type II (a) failure.

It is evident that a similar process occurs when the cutter is further into the wood. The deflection surface is formed by a failure in tension perpendicular to the grain either as a new failure in a virgin work-piece or by extension of such a failure left by the previous cut (Fig. 5). With a high cutting angle and dense, dry wood, the deflection may be small so that the shear angle remains high and the shear stress in the shear plane remains below the strength of the wood. Thus even after severance has occurred, tension stresses are superimposed on bending stresses, and the wood fails in tension parallel to the grain below the cutting plane. Hence failure may be continuous both at the cutting edge and in a plane below it.

If fiber severance occurs before Type II failure, it takes place very rapidly, freeing above and below the cutting plane highly stressed zones of wood. Above the cutting plane, shear

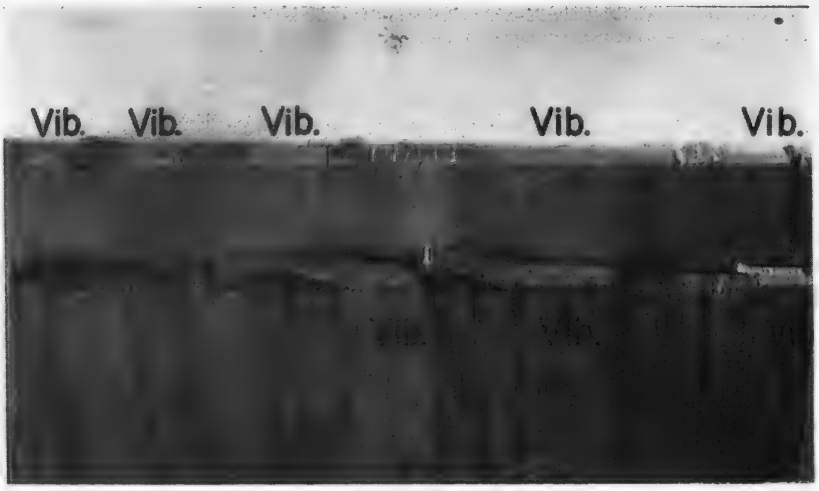

Fig. 8.—Lateral vibration at 60 c.p.s. prevented Type II failure and improved surface quality in cutting yellow-poplar (top) and common persimmon (bottom) at 0.5 in. per min. Vibration was alternately applied and removed. Cutting angle 25 deg., nominal chip thickness 0.030 in.

failures occur in rapid succession and form sub-chips. Below the cutting plane, as fiber severance proceeds, there is isolated a curved layer attached on its concave surface to a base held practically rigid by the cutter. This layer grows in depth and hence in stiffness, so that a point is reached where shear and tension stresses, resulting from its original deflection, equal the strength of the wood at the interface, and a split occurs. The deflection may be slight so that such a failure occurs only once while severance proceeds (Type I (a)) or it may be such that two or more laminae form before severance ceases and deflection commences again (Type I (b)).

Although fiber severance occurs rapidly, and the normal force may oscillate violently due to the intermittent cutting action, the parallel force usually remains relatively constant, and it is evident that the compression ahead of the cutter is not relaxed at the end of a severance phase. It appears that the sub-chip, after formation by shearing, is still subject to friction where it is in contact with the wood at the shear plane and the cutter face, so that the compressive force is maintained. Evidence concerning this is given later. It is thus apparent that the deflection phase of indentation by the cutting edge may give rise to cutting forces greater than those required to cause shear of the sub-chips and can even cause wood below the cutting plane to fail in its strongest direction.

Another implication is that the compression of the wood before the cutter results in a considerable extension across the grain in a direction parallel to the cutting edge. This violates the specification of a plane problem, and requires consideration of the third dimension. Further, in a grooving cut as in ripsawing, this lateral compression would cause increased frictional resistance at the sides.

This build-up of force is not explicable in terms of elastic or plastic theory, but is a problem that is peculiar to cellular materials. It appears to involve local compression of the wood ahead of the cutting edge, often to the point where a solid transparent zone is formed. This is considered to be an unstable process, which occurs as follows: The first cell walls met by the cutting edge may be pierced or severed, if the edge is sharp enough and the cutting angle large enough, before it is deflected sufficiently to bear against the adjacent walls. In this case, fiber severance and cutting are continuous. If not, the first row will gain normal and frictional resistance from the adjacent walls, thus increasing the probability that these two sets of walls will be deflected another cell space before they bear against the next set and gain further support. Here the situation is unstable, and the formation of a densified zone in front of the cutter has an effect of distributing the stress to a widening base. If Type II failure does not intervene, deflection is terminated by severance at the cutter edge, possibly by plastic flow of the highly compressed and heated wood at this point. A change from static to sliding friction might partly account for the rapid progress of severance.

In considering this phase of cutting, there appeared to be some analogies with the cutting of other cellular materials, such as grass, bread or meat. These materials yield greatly before an edge and offer considerable resistance to cutting unless the cutter is given a lateral motion or "draw", which may have two beneficial effects. Firstly, the effective cutting and sharpness angles become respectively higher and lower. Secondly, it is possible that minute serrations in the edge may act like teeth to tear the cell walls, for in practice a scythe blade or a meat knife is sharpened frequently with a rough stone. It appeared that the basic effect of lateral motion might be to accomplish severance of cell walls without excessive compression.

To test this suggestion experimentally, it proved convenient to introduce a lateral component into the relative motion between cutter and work-piece by vibration at 60 c.p.s. by means of a solenoid. This had the pronounced effect on chip formation shown in Fig. 8. All failure types were replaced by Type I(a) with very little delamination. The cutting process could not be observed with the microscope, but subsequent observation of the surface showed only fine splits on the cut surface, and the fraying of the edge characteristic of cutting in this direction was practically absent.

The forces measured in the x and z directions were reduced by 60 to 80 percent, and the friction values computed from them were very low, but this was to be expected. Without measurement of the third component of force it is not possible to analyze the full effects. There are many theoretical and practical implications of these few results, but those relevant to the present discussion are:

1.) The indentation stage is highly important in its effects on failure type and cutting forces, and if the deflection phase can be eliminated or reduced, the observed forces may be reduced to levels comparable with values computed from equations (3), and (4), possibly allowing for a higher strain rate. Thus the provision of a reasonably accurate analysis for the 90°–90° cutting direction is dependent on successful solution of this highly complex problem of indentation.

2). The high effective cutting angle and low effective sharpness angle associated with lateral vibration result in a high stress concentration at the edge, and further, the friction components at the shear plane and on the cutter face are less, so that the high cutting forces are not maintained after shear occurs. This is probably a more important factor than edge serration since few of these were visible at 5× magnifications in the cutters used.

3). The coefficient of friction may be generally lower related to sliding rather than the static conditions that prevail during the deflection phase

Fig. 9.—Application of SAE 30 lubricating oil (dark-stained areas) prevented Type II failure and improved surface quality in sugar maple. Cutting angle 40 deg., nominal chip thickness 0.030 in.

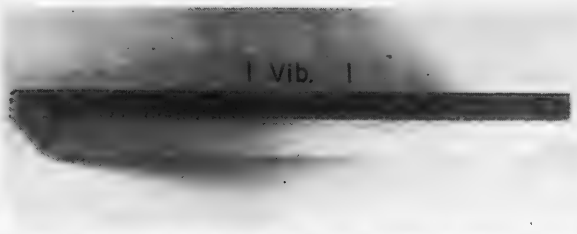

Fig. 10.—Lateral vibration at 60 c.p.s. (center section) prevented fuzzy grain in cutting at 90°–0° (planing) in eastern white pine at 5 percent moisture content. Cutting angle 5 deg., nominal chip thickness 0.015 in.

That friction plays a part in the deflection phase was demonstrated by a few cuts in which SAE 30 oil was applied to parts of the work-piece ahead of the cutter. Fig. 9 shows the effect with a 30° cutting angle in sugar maple at 5 percent moisture content. Apparently the reduction of the friction coefficient from 0.68 to 0.52 was sufficient to change the failure type from II (a) to I, and it was noted that the sub-chips snapped away separately after they were sheared. Failure type was not changed in yellow-poplar or Alaska yellow cedar at 5 percent moisture content, apparently because there was little reduction in friction coefficient. More work on these lines should be valuable in clarifying the role of friction.

4). The importance of the indentation phase has a bearing on the effect of blunting, which has largely been ignored in analyses of cutting. Voskresenski (3) gives an analysis relating pressure and friction at the edge to the cutting force, but goes no further. His analysis cutting at 90°–90° includes a force pertaining to indentation by the edge, obtained from experiments not described. A few observations were made by the author of the rate of force increase at the very beginning of a cut, and applied in an analysis different from that described above. Good results were obtained, but such empirical values have very limited application, so this approach was not pursued.

The significance of the blunting process is that a small increase in the radius of curvature of the cutting edge would prolong the deflection phase, and since it is an unstable process, cutting forces would increase much more rapidly with slight blunting than might be expected. A solution of the indentation problem should precede an attack on the problem of blunting.

As an illustration that the investigation of one cutting situation may have significance for others, and that an indentation stage may affect cutting in other directions, it is mentioned that vibration had beneficial effects on cutting in the other main directions, 90°–0° (planing) and 0°–90° (rotary veneering). In the first, higher surface quality was obtained at lower cutting angles (Fig. 10), and in the second, high surface quality (tight side of next veneer) and uniform thickness of chip were obtained when a cutting angle of 45° was used without a pressure bar (Fig. 11). These few observations also suggest that further study of such techniques to modify the cutting process may eventually have far-reaching practical results.

It is evident that the results of this study of cutting action have implications for a wide variety of problems that cannot be discussed here. A better basis is provided for the investigation of cutter wear, optimum clearance angle, surface quality, chip form as related to chip thickness, and gluing properties of end grain surfaces, to mention only a few of the many problems that may at first sight appear to have little common ground.

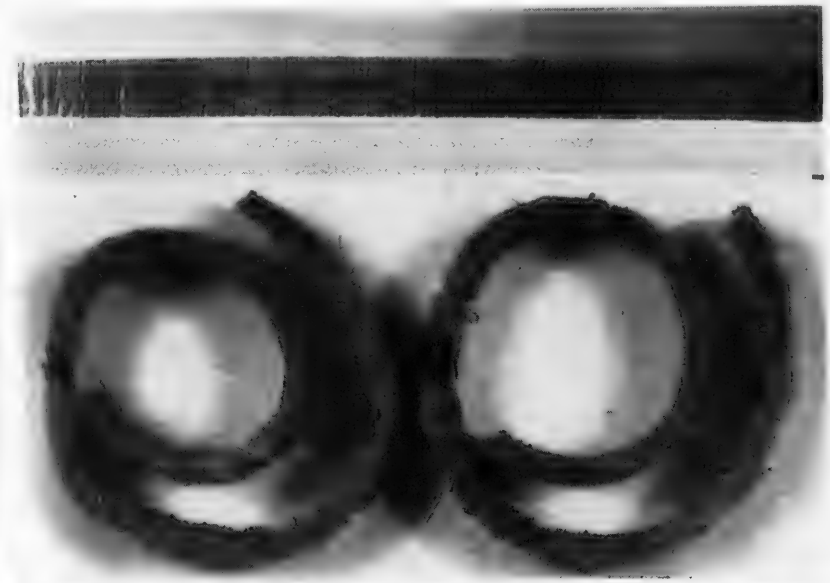

Fig. 11.—Orthogonal cutting at 0°–90° (rotary veneering) in saturated yellow birch with 30° cutting angle, 0.050 in. nominal chip thickness. Lateral vibration at 60 c.p.s. resulted in a smoother surface (top left) and a stronger chip more uniform in thickness (inner half of each chip.)

Summary

The essential action of a cutter edge on wood has been studied with the aim of finding basic concepts common to all machining processes.

Since cutting can be studied effectively only at low speeds, an experiment was undertaken to establish the effect of cutting speed on tool forces and surface quality. It was found that an increase of cutting speed from 0.5 inch per minute to 28,000 feet per minute caused a small increase in cutting forces predictable on the basis of chip inertia, with no distinguishable change in surface quality.

In an analytical study of slow-speed orthogonal cutting, attention was necessarily concentrated on a particular cutting direction, but some of the findings are significant for wood-cutting processes generally. Attempts to represent a cutting situation by an analytical model have had the effect of high-lighting areas of ignorance about wood properties as related to the cutting process.

A model for cutting with both cutting edge and velocity vector at 90 degrees to the grain, based on the theory of a beam on an elastic foundation, has proved valuable in the development of two aspects that are consid-

ered important. Firstly, equations have been derived that provide, in the normal range of cutting conditions, a satisfactory criterion for predicting failure types related to surface quality and cutting efficiency, and which indicate that moisture content is an important factor. Secondly, it has become evident that the complex indentation stage of cutting plays an important part in the cutting situation studied, and is associated with levels of cutting forces and surface damage beyond those predictable from elementary theory. This throws light on the blunting process, which indicates that edge sharpness cannot be ignored in analysis.

Further, it is apparent that friction also plays an important role. Such considerations led to the application of induced lateral vibration and to lubrication. In brief tests, surface quality was greatly improved in the cutting situation referred to above, and also in those associated with planing and rotary veneering.

The model adopted has certain limitations, and a more exact analysis for the problem of indentation of a cellular material by a rigid wedge is needed. The results of the investigations have implications for a wide variety of problems, however, and should contribute to their more effective investigation.

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Fortified Wood Preservative

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Adding 2 percent of penta to coal tar creosote increased toxic efficiency by some 40 percent. Reasoning behind the combination is to reduce the risk of early failure due to low retention in 8-pound creosoted poles without increasing "bleeders".

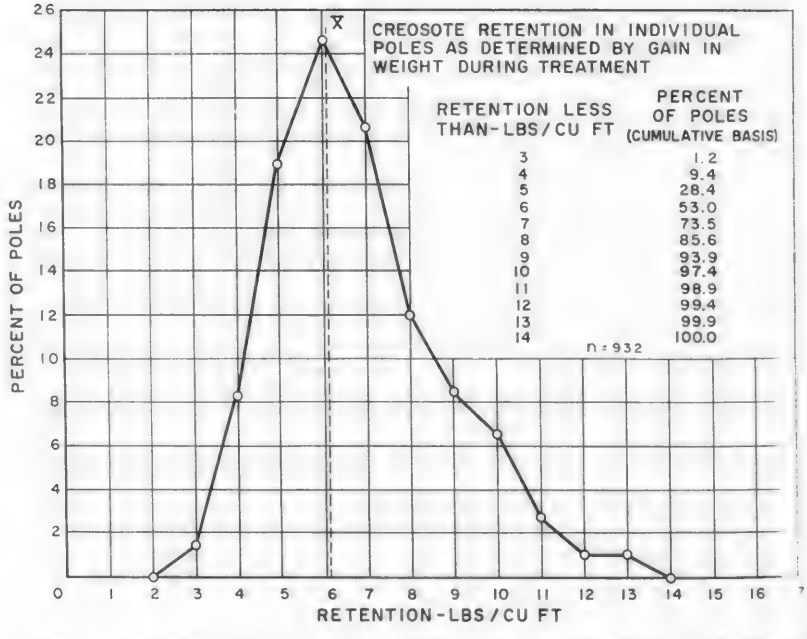

Fig. 1.—Distribution curve of creosote retentions—gain in weight basis—in 932 freshly treated 8-pound empty-cell Southern pine poles. Data also arranged in tabular form on a cumulative basis.

[1] Presented at Session II, Wood Preservation, FPRS 14th National Meeting, June 5–9, 1960, Montreal, Canada.

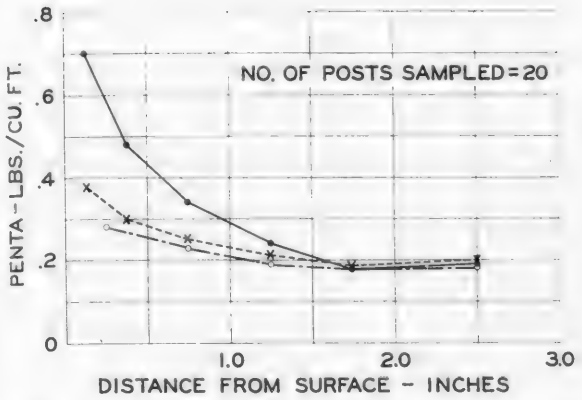

Fig. 2.—Distribution of penta in pole-diameter Southern pine posts after 8-pound penta-petroleum (5%) treatment, Plant A. Solid line—immediately after treatment; dashed line—after 2 years in Orange Park plot; broken line (open circles)—after 4 years in Orange Park plot.

Fig. 3.—A typical penta-petroleum bleeder. This Southern pine pole was treated to a nominal 8-pound gauge retention by empty-cell process.

for Southern Pine Poles[1]

CLEAN, DURABLE WOOD POLES are required today by most telephone and power utilities. Poles made from those species recognized in the American Standard Specifications and Dimensions for Wood Poles 05.1–1948 and approved by the National Electrical Safety Code are being produced at the rate of 5 to 7 million units a year. (1)[2] Under present critical use requirements, not all of these poles are acceptable for immediate unrestricted urban and suburban installation. The delivery of "bleeders", even one or two per carload, poses a real problem to the field forces charged with setting poles because dirty or bleeding poles are not tolerated in most communities today. Further, as might be expected, unclean poles are not attractive to the linemen and installers who must climb them.

On the other hand, should the physical life of the pole be sacrificed for cleanliness? The performance of 8-pound creosoted southern pine poles is in some cases marginal (2) (3). Study of Fig. 1 which shows the creosote retention in 932 individual 8-pound southern pine poles, sheds much light on this problem. Too many "8-pound" poles are treated at risk retention levels; that is, 28.4 percent have retentions less than 5.0 pounds per cubic foot. There are reasons to believe also that southern pine poles treated with 8 pounds of pentachlorophenol-petroleum solution per cubic foot might behave somewhat similarly and that their performance could be influenced by the movement (4) of the whole penta-petroleum complex outward and into the surrounding soil (see Fig. 2 and 3).

In Fig. 2 is shown the average losses after two and after four years of exposure from the below-ground sections of a typical group of pole-diameter southern pine posts treated with penta-petroleum (5 percent solution) and installed at the Laboratories' Orange Park, Florida test plot. From bioassay data it may be predicted that when the penta retention falls below 0.25 pound per cubic foot in its outer periphery, the pole is in jeopardy. Critical examination to date of the test posts represented by these curves and other similar groups tends to confirm the bioassay results.

Losses of the penta-petroleum solution are possibly explained by Fig. 3. This, while not a typical penta-petroleum-treated pine pole, is a typical bleeder of this type treatment. By analysis, the surrounding soil is high in chloride due to errant preservative.

It is the purpose of this paper to discuss the possibilities of using, at the same 8-pound retention level as for creosote or for 5 percent penta-petroleum, a solution comprised of coal tar creosote to which commercial grade pentachlorophenol has been added. Tests indicate that this can be done successfully, thereby providing about 40 percent increase in toxic effectiveness without increasing the liquid preservative retention; in other words, without increasing the tendency of the treated poles to bleed. Even under the best of circumstances, an occasional bleeder and possibly a poorly treated pole may slip through with this fortified treatment, but basically, as far as the charge of poles as a whole is

[2] Numbers in parentheses refer to the Literature cited at the end of this report.

concerned, both the objectives of durability and cleanliness are achieved at one and the same time.

Putting Theory Into Practice

For over 30 years, there has been a constant and aggressive search by Bell Telephone Laboratories and others for a low-cost wood preservative that 1) penetrates the sapwood satisfactorily, 2) is well distributed in the sapwood at a sufficiently high retention level—as determined by analysis of the wood—to remain effective in service for many years, and 3) leaves the surface of the treated wood clean. This implies that the pole surfaces will be clean upon removal from the treating cylinder, during subsequent handling by the line crews, and during the entire service life of the pole in line. These are the three basic criteria in what has become to be known as "Results-Type Specifications"(5). In addition, the preservative should not affect the strength adversely or decrease the electrical resistance of the wood, nor should it harden the pole surface so much as to influence climbability. It goes without saying that this preservative from the treater's standpoint must be:

1. capable of being handled in the customary treating equipment, that is, same pressures, temperatures, and so forth;
2. relatively free from sludging and emulsification characteristics;
3. non-toxic, when properly handled, to man and animals;
4. adapted to treatment of green, steam-conditioned poles;
5. relatively non-flammable, and
6. stable and will remain in balance (little or no selective absorption, or alteration in concentration) during constant use.

It would be a major undertaking to list all of the experimental and commercial attempts made in the last three decades to obtain clean poles with all the desired traits. Some involved the use of either new water-borne or oil-borne preservatives, some the introduction of additives that would alter the viscosity characteristics of the preservative after it has entered the wood, and some modified treating techniques. During the critical shortage periods at the time of and subsequent to World War II, a few preservatives were introduced that opened new possible horizons in the search for clean

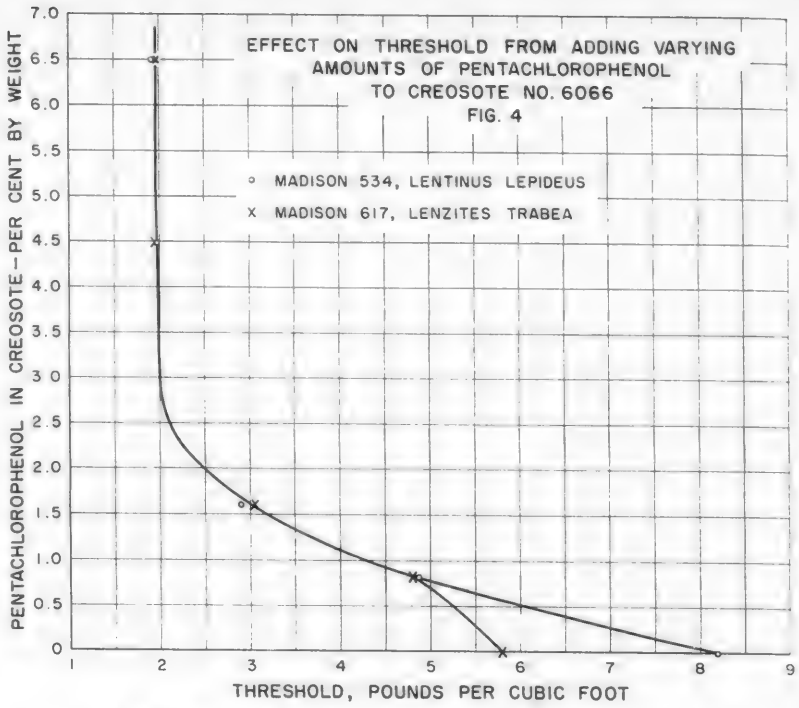

Fig. 4.—Effect on threshold from adding amounts of pentachlorophenol to a typical domestic creosote, No. 6066.

preservatives. While highly promising combinations of creosote and 5 percent pentachlorophenol in petroleum, (6) mostly at a 50/50 ratio, did cause some insurmountable difficulties during regular commercial treatments, they did provide, under certain conditions of careful plant operation, clean, durable southern pine poles. Soil-block bioassays at Madison (7) demonstrated that these combinations were effective wood preservatives, and this has been confirmed by line experience because to date no pole in Bell System lines properly treated with the 50/50 combination has been reported as decaying because of preservative failure, and yet many thousands of these poles were installed as far back as 1942. This treatment is still being used successfully in the Los Angeles area today on Douglas-fir poles. Conversely, it has been the experience that some poles treated as recently as 1946 with 50/50 mixtures of creosote and non-toxic petroleums—without fortification—have failed even in the northern latitudes of Michigan and the New England States. These, and other considerations about to be described, lead inevitably to the idea of combining creosote and technical grade pentachlorophenol and to discarding the non-toxic petroleum as a constituent. This combination comes nearest to meeting the requirements stipulated for the ideal preservative.

That the Bell Laboratories ha been thinking of combining tox constituents of wood preservativ for some time was evidenced by th submission through their represent tive, J. Leutritz, Jr., of a preliminar draft specification for creosote to th Preservatives Committee of the American Wood-Preservers' Associa tion on January 6, 1948. This draft specification stated, "The creosote when assayed biologically, using the fungus *Lentinus lepideus*, shall ex hibit a threshold concentration of not more than 3 pounds per cubic foot", and "If the creosote does not assay up to the limits set, (it) shall be fortified—with 2.5 percent penta chlorophenol or 0.125 percent cop per naphthenate - - -". In theory it was considered that any wood preservative—in this case, creosote could be mixed with other recog nized wood preservatives to form a super preservative, let us say, that would assay up to certain standards biologically as many drugs, like vi tamins, are called on to do today.

In the present combination, th choice of coal-tar creosote as th carrier was well considered. Cre sote is toxic in its own right, con taining some 160 single compound that have been isolated thus far, an creosote is far superior as a solven for pentachlorophenol to any of th reasonably priced, commercial p troleums known to date. Anoth factor is that both creosote and pen are readily available at the treatin

plants of most of the contract suppliers of southern pine poles.

First commercial treatments with the new creosote-pentachlorophenol solution were made experimentally at the plant of the Eppinger and Russell Company, Jacksonville, Florida, in the fall of 1953. As a matter of expedience, these treatments were initiated with an imported creosote of vertical retort origin (#6011 on Fig. 5), to which technical grade penta was added, and at a 6-pound, by gauge, retention level. In 1954, when the supply of vertical retort creosote at the treating plant had become exhausted, a switch was made to creosote conforming to Bell System Specification AT–7315, "Coal Tar Creosote" (somewhat similar but a little more restrictive than AWPA Standard P1–54). Later, when the new Specification AT–7697 covering the treatment of southern pine poles with the new fortified preservative was issued on February 4, 1957, the change-over to creosote-penta solution was completed at all southern pine plants that treat for System use.

The AT–7697 Specification calls for coal tar creosote per Specification AT–7315, and 2 percent pentachlorophenol by weight, that meets the requirements of AWPA Standard P8, "Standards for Oil-Borne Preservatives, 1. Pentachlorophenol". In addition, the new extraction method was required as the means of determining retention. This "assay" method is the outgrowth of test plot studies and investigations made on poles removed from line.

These studies clearly indicate that well-penetrated poles perform in accordance with their actual "in-the-wood" preservative retention as determined by solvent extraction, and not necessarily in accordance with retentions determined by plant gauge readings (8). Not less than 6.0 pounds per cubic foot in the composited sections from the outer 0.5 to 2.0 inches of 20 increment cores from 20 representative poles was required. This still is the retention criterion. This *6.0 pounds by extraction* has been regularly obtained by several plants this past year when treating steam-conditioned southern pine poles with 8 pounds per cubic foot by gauge. It is estimated that by the fall of 1960, at least one million southern pine poles treated with creosote-penta will have been produced for Bell System use.

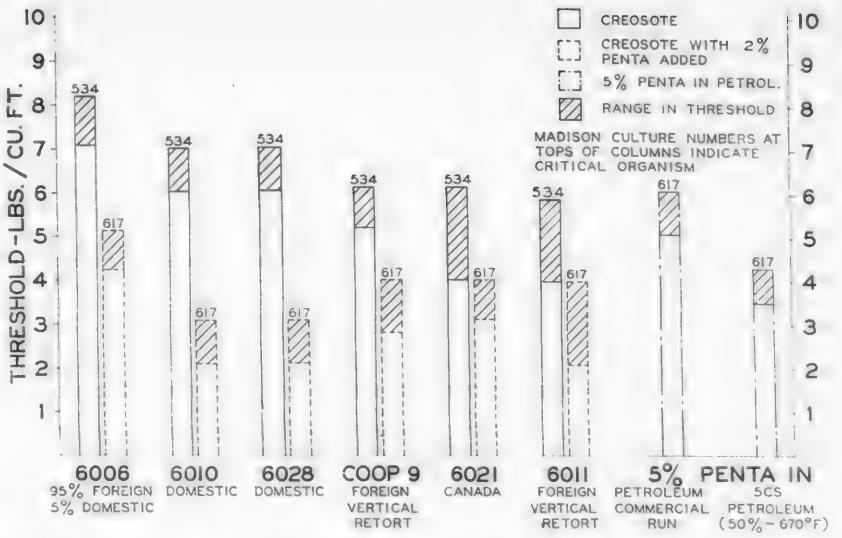

Fig. 5.—Bioassay threshold values of creosote, penta, and creosote-penta solutions.

Laboratory and Test

The idea of combining two or more wood preservatives is not new. It will be recalled, for example, that the Allardyce process (9) consisted of pressure treating with a zinc chloride solution followed by a second pressure treatment with creosote. The Card process (9) too, combined a zinc chloride solution (80 percent) with creosote (20 percent) in a single pressure treatment. During the critical shortage period associated with World War II, pine poles were pressure treated full-length with ZMA or with chromated zinc chloride, followed with a butt treatment of creosote. It is our conviction, however, that the deliberate combining of two recognized toxic materials based on the results a) of studies of what specific organisms cause decay in southern pine poles and b) of laboratory soil-block bioassay tests is new (10). In addition, the amount of material to be added has carefully been considered in bioassay studies so that the maximum amount of effectiveness is obtained at the most reasonable cost.

Perhaps a bit of background describing the manner in which the Bell Laboratories conducts wood preservative research and development is in order. In discussing these techniques, the creosote-penta preservative will be used as the subject under scrutiny. Ever since the inception of the studies of wood preservatives at the Laboratories in 1925, a program has been followed that today is referred to as the Four-Phase Testing Program (8)(11). New preservatives, either when offered as proprietary compounds or when conceived in our own laboratory, must follow this established four-phase routine. The four phases are:

1. Laboratory soil-block bioassay
2. Outdoor exposure tests of ¾-inch sapwood Southern pine stakes
3. Exposure tests of pole-diameter test posts
4. Experimental poles in line.

How this program works as applied to the study of creosote-penta follows:

Phase I—Laboratory Soil-Block Bioassay

The study of the new combination began in the laboratory. It was demonstrated (12) by bioassay that the creosote-penta solution was highly effective, and that this combination should be studied further. It became necessary then to determine the actual amount of penta required to give the most effective results biologically. In accordance with procedures quite similar to those now incorporated in ASTM Standard D-1413-56T (13), southern pine sapwood blocks were treated with a domestic coal tar creosote ‡6066 and with creosote ‡6066 to which varying amounts of penta were added. The blocks were then weathered, and after being brought to equilibrium in an incubation room (80°F, 70 percent RH), they were inoculated with the appropriate organism —either *Lentinus lepideus,* Madison 534, or *Lenzites trabea,* Madison 617. The results expressed as threshold[3] in pounds per cubic foot follow:

[3] Threshold is defined as the minimum amount of preservative that is effective in preventing decay, under the conditions of the test, by a particular fungus.

Preservative and concentration	Organism	
	Madison 534 (Threshold—pounds per cubic foot)	Madison 617 (Threshold—pounds per cubic foot)
6066 alone	8.20	5.80
6066 plus 0.83% penta	4.87	4.80
6066 plus 1.61% penta	2.90	3.06
6066 plus 4.49% penta	1.96	1.95
6066 plus 6.52% penta	1.91	1.96

These data show that the most effective concentration falls between 1.61 percent and 4.49 percent (see Fig. 4). It could be argued that little is to be gained (possibly one pound per cubic foot) from using more than 1.61 percent penta, and it is readily apparent that percentages above 2.75 are unnecessary biologically. A 1.61 percent concentration yields a drop in threshold from 8.2 to 2.9 pounds (a 65 percent drop) for Madison 534 and from 5.8 to 3.1 pounds (a 47 percent drop) for Madison 617. Rather than set 1.6 pounds as the minimum penta content, it was decided to specify the more conservative 2.0 percent penta addition, and this was done.

It was realized also that the pentachlorophenol, being a chemical compound and not a complex mixture of compounds, provided a rather consistent amount of biological effectiveness, and that most of the variation in threshold results could be attributed to variations in the properties of the creosote used in the test. (Compare the several left hand bars representing straight creosotes in Fig. 5.)

Many soil-block bioassays have now been run on creosote-penta solutions. Some of the results are shown graphically in Fig. 5. It should be kept in mind that the lower the threshold, the more effective the preservative. In the twin bars on the left, Preservative ‡6006 made up of foreign creosote (95 percent) and domestic creosote (5 percent) took 7 to 8 pounds per cubic foot to prevent attack by "Madison 534", *Lentinus lepideus*. The cross-hatched portions of the bars indicate the experimental range of performance, and so the threshold is set at between 7 and 8 pounds. On adding 2 percent penta, by weight, to this creosote, the threshold dropped to between 4 and 5 pounds per cubic foot. This means that the threshold was reduced 3 pounds per cubic foot by adding penta to the creosote. It should be noted that, when penta is added, the critical, most tolerant test organism then is "Madison 617" *Lenzites trabea*.

Lentinus lepideus is one of the most common enemies of standing creosoted southern pine poles according to a study made in cooperation with the U. S. Forest Products Laboratory at Madison, Wis. Some of the early results were reported by Snoke (14) in 1957, and these emphasized the importance of *Lentinus lepideus* as a creosoted pine pole destroyer. Further evidence is now being accumulated that indicates, however, that pine poles are attacked by a variety of wood-destroying fungi. Madison 534 is the most tolerant organism with straight creosote, but Madison 617 becomes the critical organism after penta is added. This leads to the conclusion that several specific organisms can be controlled by combining toxic ingredients.

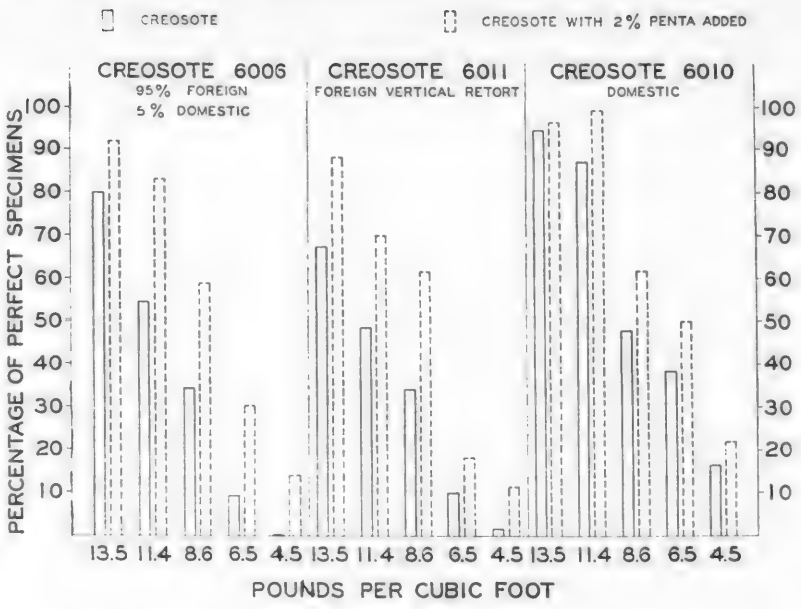

Fig. 6.—Performance of ¾-inch treated Southern pine stakes after 4 years in the Orange Park, Florida, test plot.

With Preservative ‡6010, a domestic creosote—the second group of twin bars from the left on Fig. 5—the same reaction takes place. Six to seven pounds per cubic foot controls *Lentinus lepideus:* and when 2 percent penta is added, the threshold drops to two to three pounds, a reduction of 4 pounds per cubic foot. The critical organism again becomes *Lenzites trabea* when penta is added. The same pattern holds with another domestic creosote, ‡6028. The preservative shown as "Coop 9" is a vertical tar creosote imported from the United Kingdom. The results are similar. Preservative ‡6021 was produced by the Dominion Tar and Chemical Company and was supplied by the Bell Telephone Company of Canada; the same result is noted when 2 percent penta is added: the threshold goes down.

Number 6011 designates another foreign vertical retort tar creosote (that used in the early treatments of poles at Jacksonville in 1953); this creosote performs about the same as "Coop 9" both before and after the addition of 2 percent of penta.

The next bar to the right—a single bar—illustrates what happens in soil-block bioassay to a typical commercial 5 percent penta-petroleum preservative. The performance is about at the level for the average creosote illustrated. It has been found that the performance of penta varies with the characteristics of the petroleum distillate used as solvent (15). The single bar at the extreme right gives the threshold results when a very high-boiling distillate petroleum containing 5 percent penta is assayed. The performance is quite good; the threshold lies between 3.5 and 4.5 pounds. The practical difficulty here is that this particular petroleum is abnormally heavy and is known to yield test posts, at least, that are very bad bleeders. If one looks at Fig. 5 objectively, it will be noted that the thresholds for coal tar creosote average somewhere around 6 pounds per cubic foot, but when 2 percent of penta is added, the thresholds drop to 3.5 or 4.0 pounds per cubic foot. This amounts to a 30 to 40 percent increase in effectiveness for the combination over that when creosote or penta-petroleum are used separately.

Recently, tests have been made the creosote-penta solutions in use several of the plants that treat poles under contract. The latest data were computed by the statistical method described by Snoke (16) in Applied Microbiology. Three of these bioassays are reported herewith:

Sample No.	Penta content		Test organisms (Madison No.)	Threshold (pounds cubic foot)
	By lime ignition (percent)	By copper pyridine (percent)		
6069	2.19	1.98	617	4.2
			534	3.0
6070	1.80*	1.98	617	3.9
			534	3.8
6071	2.37	2.18	617	4.1
			534	3.0

*Nonconforming.

The thresholds for *Lenzites trabea*, Madison 617, average about 4 pounds per cubic foot and for *Lentinus lepideus* Madison 534, somewhat lower. These data indicate that these three commercial preservatives, selected during a routine check-up, are running at the expected threshold level and that the critical or tolerant organism after the penta addition is Madison 617, *Lenzites trabea*.

Phase II—¾ Inch Stakes

Phase II of the Laboratories' program consists of the exposure in test plots of ¾-inch-square southern pine sapwood stakes. Creosote-penta treated stakes have been under test since 1953. The results to date are shown in Fig. 6. Care must be exercised in reading this figure after examining Fig. 5. The techniques involved in stake testing are covered by a tentative standard, "Method for the Evaluation of Preservatives by Means of Small Stakes" recently approved by Subcommittee XIII of ASTM Committee D–7 on Wood. In the stake tests, in contradistinction to the soil-block tests, the high value excels. This is because the index of goodness, that is, the percentage of perfect specimens, is the criterion.

Creosote #6006, the bioassay performance of which was shown in Fig. 5, behaved as follows in the ¾-inch stake tests: At 13.5 pounds retention, the percentage of perfect specimens is about 80 percent, but when 2 percent of penta is added, the percentage perfect moves up to 90. At 11.4 pounds, the percentage perfect is 55, but when 2 percent of penta is added, the percentage increases to 85 percent. The pattern is essentially the same at any given retention level regardless of the creosote employed.

Phase III—Pole Diameter Test Posts

Studies of pole-diameter test posts in test plots are well underway, but it is too early to report critically on the performance of these specimens at this time. All posts were sound on the last inspections in 1959.

Phase IV—Poles in Line

Lines of "experimental" poles are being established at several locations east of the Rocky Mountains between Canada and Mexico in the areas where southern pine poles are normally distributed. Several of these lines are being set up in the southern states where decay conditions are considered to be more severe than in the Northeast or Midwest. Reports of the performance of these poles will become available as time passes through regular channels such as reports of the American Wood-Preservers' Association Committee U–4, "Pole Service Records".

Commercial Operation

There is still much information to be obtained to satisfy all the requirements of the Four-Phase Testing Program completely. The information received to date has been amply sufficient, however, to warrant proceeding on a broad-scale commercial basis. Fitting any new wood preservative into regular plant production, of course, usually entails some problems, both technical and commercial. The days are past when the average treating plant carries only one or two standard preservatives. Many plants now treat with creosote, creosote-coal tar or creosote-petroleum, penta-petroleum, and a salt-type wood preservative. In addition, some plants treat with fire retardant solutions. The fact that there are so many preservatives kept in regular supply adds to the problems of the treater.

Today, with rigid specifications to follow, it behooves the treater to have separate lines from each treating tank to the cylinder—even separate pumps are sometimes advisable—in order to keep the cleaner preservatives uncontaminated. It has been customary in the past at some plants to use the same common lines, manifolds, and headers regardless of whether poles, ties or piling were being treated. This system operates satisfactorily for the most part when extra precautions are taken to "blow lines" carefully after each treatment, and when there is no human error involved. If the lines are unlevel or bowed vertically, however, or if the cylinders are tilted or warped, or if large amounts of preservative are pocketed, then trouble ensues more often than not because of cross-contamination. The clean preservatives will become dirty and oftentimes will fail to pass specifications. Low-quality preservatives will be enriched and the high-quality, higher priced preservatives will have to be downgraded. With the cleaner creosote-type preservatives used for poles, increases will take place in specific gravity, in distillation residue above 355°C, in material insoluble in benzol, and in coke residue. With marked increases in water content of the preservative—due essentially to steam-conditioning and subsequent empty-cell treatment of green poles—the whole situation is aggravated. It is only fair to admit that some of these difficulties have been reported when the new creosote-penta solution is used, but basically the same can be said of all oil-type preservatives. Good plant operation is a vital necessity for clean, efficient production.

Plant operational rules and regulations have no part in results-type specifications, but recognition of some of the things that should be done and those that should not must be recognized by the treater himself if he is to feel satisfied that he is treating to the best of his ability, is producing the pole defined under the specification, and is satisfying his customer as well. This can be accomplished best by the use of separate piping from the treating tank to the cylinder and by keeping the preservative low in water content—less 3.0 percent—by means of dehydration, or by the use of drier poles. Now that most treaters have recognized these facts, the difficulties attendant to conforming to specifications have been minor, and the poles have been very well treated, and for the most part they are clean. Regular and continued cleanliness, however, requires, as with straight creosote and with penta-petroleum solutions, constant vigil both on the part of the treating engineer and the inspector.

Some reports of abnormal corrosion of treating-plant equipment, presumably an adjunct of the creosote-penta preservative, have been received recently. Studies are being conducted currently to determine whether this corrosion is inherent in the new combination or whether it is associated with other aspects of treating-plant operation such as high water content, kick-back of sap, resin and allied materials from the green poles, or other phenomona that may be associated with the empty-cell treatment of steam-conditioned southern pine. The outcome of these studies will determine whether or not any special precautions are desirable when treating with creosote-penta. It should be borne in mind that most—some 85 percent—of the contract suppliers that treat with creo-

sote-penta have had no corrosion difficulties; in fact, the Jacksonville plant reports after 7 years of creosote-penta operation no corrosion problems over and above those which usually occur with steam-conditioned green poles.

The question arises occasionally as to whether or not there are any problems associated with dissolving penta in the cerosote. In making up the solution (17, 18), the penta actually dissolves more readily in creosote than it does in petroleum. This is to be expected, of course, because of the high solubility of penta in the hot, aromatic coal tar derivatives.

No problems have been reported concerning the handling of the solution in pipe lines, pumps, or in treatment generally. The solution appears to have practically the same characteristics as straight creosote.

From the standpoint of safety and health, the normal precautions usually taken in handling creosote and chemicals of the pentachlorophenol type are recommended for the combination. Since both materials have been used at plants for many years without undue risk, no health hazards are contemplated in handling creosote-penta, let alone in handling the treated product. Olafson and Leutritz (19) carried out highly convincing tests that show the combination is relatively non-toxic to cattle, and that the formation of chloronaphthalenes capable of causing hyperkeratosis, (X Disease) did not take place during treatment of poles with 2 percent of penta in creosote.

To facilitate the use of this preservative combination by others, data have been provided to the American Wood-Preservers' Association through their Committee P–4 "New Preservatives" detailing the information necessary for this committee to give consideration to making this preservative an Association Standard. This information became available to the Association at the Annual Meeting in New York in April 1960, is now in preprint form, and is to be published in the report of Committee P–4 in the Proceedings of the Association Vol. 56, 1960.

Cost

The basic increase in cost for creosote—2 percent penta treatment is reflected in the cost of the added pentachlorophenol. This has been calculated to be about 3-½ cents per cubic foot of wood treated, which appears to be well worth the value received in bringing about a higher level of performance through elimination of the risk poles with marginally low retention. Of course, to this basic increase must be added charges for new pipe lines, if required, or other facilities that might prove essential to the production of clean, well-treated poles. Such charges would obviously vary from plant to plant. Direct cost comparisons are difficult to make because two other improvements have been introduced simultaneously in the equation—a) the introduction of the assay method, and b) a new inspection control procedure that places the responsibility for quality directly on the supplier.

Resumé and Conclusions

Early failures of 8-pound creosoted southern pine poles are being reported at a higher rate than was originally presumed, particularly in the South. To reduce the number of low-retention (risk) poles, either a higher overall retention or the use of a more toxic preservative is indicated. By adding two percent, by weight, of pentachlorophenol to coal tar creosote, the toxic efficiency is increased some 40 percent over that obtained by using either creosote or penta-petroleum alone. This added toxicity will take most individual poles with low retentions out of the risk class. The chance of bleeding is still minimized because the liquid retention level is not increased.

The added efficiency of creosote-penta has been demonstrated repeatedly by laboratory soil-block bioassay. Comparative tests in outdoor plots in the South with ¾-inch sapwood stakes further confirm those findings. Tests on pole-diameter posts and poles in line are also favorable, but the period of service admittedly is short for the creosote-penta combination as such. Pole line performance of the 50/50 creosote-penta-petroleum mixture has been excellent since 1942, however, and should presage even better performance for the new preservative.

All southern pine poles for Bell System use are now being treated with this new preservative under a "results-type" specification. To date, approximately one million poles have been treated with creosote-penta solution and shipped to all states east of the Rocky Mountains. The general features of creosote-penta treatment are the same as those for straight creosote treatment. Creosote-penta poles are similar in surface appearance to poles treated to an 8-pound gauge retention with straight creosote. The elimination of early and costly failures of southern pine poles without increasing the risk of getting dirty poles is being accomplished by the use of the creosote-penta solution.

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Collapse in Some Eucalyptus after Treatment in Inorganic Salt Solutions[1]

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Collapse was increased markedly when the wood was affected chemically, but not when effect was mainly physical. Loss of lignin and hemicellulose in basic solution also increased non-recoverable collapse.

CONSIDERABLE REDUCTIONS of collapse (8, 9, 16)[2] have been reported by Chudnoff (3, 4, 5) in the sapwood of *Eucalyptus camaldulensis*, grown in Israel, after it was soaked in dilute hydrochloric acid and in dilute acidified solutions of sodium chloride and zinc chloride. On the other hand, a considerable amount of work on chemical seasoning has never shown any evidence of useful reduction of collapse in Australian timbers after they were soaked in solutions of sodium chloride, urea and other compounds. The same negative result was found by Ellwood (7) with *E. regnans* veneer.

Runkel (13) suggested that the inception of collapse may be related to the proportions and distribution of chemical constituents in the cell wall.

The present work was designed to test the effect of immersion in inorganic salt solutions on collapse in *E. camaldulensis* and *E. regnans*. In addition, the relation between collapse and some chemical constituents of the cell wall was explored by drying *E. regnans* wood extracted with sodium hydroxide and sodium chlorite.

[1] A contributed paper, received August, 1959.
[2] Numbers in parentheses refer to the literature Cited at the end of this paper.

Experimental Procedure

Treatment of E. camaldulensis (Dehn.) in Inorganic Salt Solutions: Material of this species was available only in the air-dry state. One-half inch cubes were prepared from sapwood and heartwood of three Australian and three Israeli trees, and were soaked in distilled water under alternating vacuum and atmospheric pressure until saturated. Two heartwood and two sapwood specimens from each of the six trees were allotted at random for treatment in each of the salt solutions listed in Table 1.

The specimens were immersed in the various solutions for 30 days, then dried at low temperature and steamed for 2 hours to "recondition". They were then again immersed in the solutions for 8 days, sealed on the end grain with nitrocellulose lacquer, and dried at 150°F dry bulb and 144°F wet bulb temperature. After another recondition-

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TABLE 1 RESULTS OF DRYING TESTS WITH ½ I.N. CUBES OF E. CAMALDULENSIS GROWN IN AUSTRALIA AND ISRAEL

(Per cent. total shrinkages in oven-dry state based on green dimension)

Type of Wood	Solution	Total Shrinkage Before Reconditioning (per cent.)				Total Shrinkage After Reconditioning (per cent.)			
		Tangential		Radial		Tangential		Radial	
		Australia	Israel	Australia	Israel	Australia	Israel	Australia	Israel
Sap	Aq. dist.	14.6	9.6	7.0	5.9	10.2	6.3	5.4	4.0
	0.01N HCl	24.5	16.8	10.7	8.4	21.2	15.5	10.1	8.2
	1.5N NaCl	10.4	7.6	4.8	4.0	7.7	4.9	4.0	2.8
	0.07N $ZnCl_2$	19.5	14.7	8.6	9.3	15.4	12.4	7.6	8.4
	0.74N $ZnCl_2$	20.7	16.2	8.1	9.4	18.0	13.9	7.5	8.4
Heart	Aq. dist.	19.6	14.8	11.0	10.6	9.9	7.3	5.7	5.4
	0.01N HCl	24.0	25.9	14.4	15.9	20.4	22.9	13.4	14.8
	1.5N NaCl	17.5	14.8	7.9	8.1	11.1	7.8	5.6	5.3
	0.07N $ZnCl_2$	22.7	27.3	11.7	14.3	17.3	19.3	9.3	12.2
	0.74N $ZnCl_2$	19.8	29.0	9.7	12.8	15.8	23.3	8.4	10.1
Significant differences between two means									
5 per cent. level		4.9		3.4		4.8		2.7	
1 per cent. level		6.6		4.5		6.5		3.5	

Australia - Material grown in Australia. Israel - Material grown in Israel.

ing treatment, they were oven dried in air at 220°F. The double immersion treatment was designed to ensure complete penetration of the salt in this initially air-dry material. Control specimens were immersed in water for 30 days and then dried and reconditioned.

Shrinkages were determined at 12 percent moisture content before and after reconditioning, and were extrapolated to the oven-dry state, by means of the linear dependence of shrinkage on moisture content established for salt-impregnated wood by Stamm (15).

Treatment of E. regnans (F.v.M.) in Inorganic Salt Solutions: One inch cubes from the heartwood of two trees of *E. regnans* were allotted at random to the treatments shown in Table 2 and immersed green from the saw for 67 days. Each treatment included two specimens from each tree.

After immersion, half the number of specimens were end-sealed, and all specimens were then dried at 150°F dry bulb and 144°F wet bulb temperature, oven dried at 130°F under approximately a 27 inch vacuum, reconditioned (after conditioning to a moisture content of about 17 percent) and finally oven dried in air at 220°F. Shrinkages were measured in the oven dry state. Selected specimens were analyzed for salt retention. The collapse-free shrinkage was measured on thin cross-sections of 1/32-inch length in the fiber direction (8) and corrected for salt retention (15).

Extraction of E. regnans with Sodium Hydroxide and Sodium Chlorite: Cubes 0.4 inch were treated in 0.5N solution of sodium hydroxide at 65°F for periods of up to 2 weeks, and at 300°F for up to 6 hours. Some additional material, including microtome sections 200μ thick radially, was treated in 0.1N and 0.5N NaOH for up to 17 hours. Control specimens were immersed in distilled water at 65°F for 4 days, and at 300°F for 4 hours.

Microtome sections were also treated in 0.25 percent sodium chlorite solution at 158°F for up to 7 hours by the method described by von Koeppen and Cohen (10), which ensures extraction of most of the lignin after 4 to 6 hours without greatly affecting the hemicelluloses. Control specimens were treated in distilled water under similar conditions.

Each of the above tests included either 3 or 6 specimens. Immediately after the completion of immersion, all specimens were air-dried and shrinkages were measured at 12 percent moisture content before and after reconditioning.

A few specimens were analyzed for lignin content after extraction by the method given by Ritter, Seborg and Mitchell (12), with some modifications developed at the Division of Forest Products, C.S.I.R.O. (unpublished data). Pentosans were estimated in matched samples according to the method described by Doree (6), except that thiobarbituric acid was used instead of phloroglucinol as the precipitant (*cf.* 11).

Results

Treatment in Inorganic Salt Solutions: The total shrinkages[3] in the oven-dry state observed in *E. camaldulensis* before and after reconditioning are summarized in Table 1. None of the treatments investigated caused a significant reduction in total shrinkage, but immersion in 0.01N hydrochloric acid and in either 0.07N or 0.74N zinc chloride solution resulted, in many cases, in significant increases, compared with the water-treated control specimens. The significant differences between any two means are included in Table 1. In general, Israeli material shrank and collapsed to a smaller extent than Australian material, but the heartwood of the former was more strongly affected by hydrochloric acid and zinc chloride.

Table 2 gives the results obtained with *E. regnans* heartwood. In addition to total shrinkages, the table contains recoveries in percentages of total collapse and observed salt retentions expressed in percentages of the theoretical value, calculated by successive approximations from the relation

$$W_s = c\,(V_g - \frac{W_o}{d_o})\ (g)$$

where W_s = weight of salt retained in specimen (g)
c = salt concentration in solution (g/cc)
V_g = observed green volume of specimen (cc)
W_o = oven-dry weight of specimen (corrected for salt retention) (g)
d_o = density of wood substance (g/cc), taken as 1.5.

Statistical analysis of the results for *E. regnans* showed no significant differences in total shrinkages before reconditioning except for treat-

[3] Total shrinkage is defined as the sum of the total collapse and the "normal" (collapse-free) shrinkage determined on specimens 1/32 inch in the fiber direction (8).

TABLE 2 RESULTS OF DRYING TESTS WITH 1 IN. CUBES OF E. REGNANS (HEARTWOOD) GROWN IN AUSTRALIA
(Per cent. total shrinkages in oven-dry state based on green dimension)

Solution	Total Shrinkage before Reconditioning (per cent.)		Total Shrinkage after Reconditioning (per cent.)		Recovery in per cent. of Total Collapse		Salt Retention in per cent. of Theoretical Value
	Tangential	Radial	Tangential	Radial	Tangential	Radial	
Untreated	25.1	18.2	12.7	9.4	87	78	-
Aq. dist.	27.6	19.5	14.0	9.5	64	78	-
0.0002N HCl	25.4	17.5	12.6	8.5	76	84	-
0.1N NaCl	27.1	18.0	13.8	8.7	75	80	66
0.1N NaCl + 0.0002N HCl	24.7	17.8	13.7	8.4	78	83	57
N NaCl	27.2	15.5	11.7	6.6	91	98	78
N NaCl + 0.01N HCl	27.2	16.1	13.0	6.8	84	96	59
0.2N $CaCl_2$	26.7	16.1	14.5	8.6	74	82	51
0.2N $CaCl_2$ + 0.0002N HCl	28.2	17.3	13.8	8.4	79	84	44
Saturated $NaHCO_3$	39.8	24.0	25.2	14.6	48	52	70
Saturated $NaHCO_3$ (1000 lb/in.^{2})	40.6	25.2	34.6	20.5	20	26	70
Significant differences between two means							
5 per cent. level	3.7	3.5	2.5	2.2	-	-	-
1 per cent. level	5.0	4.7	3.5	2.9	-	-	-

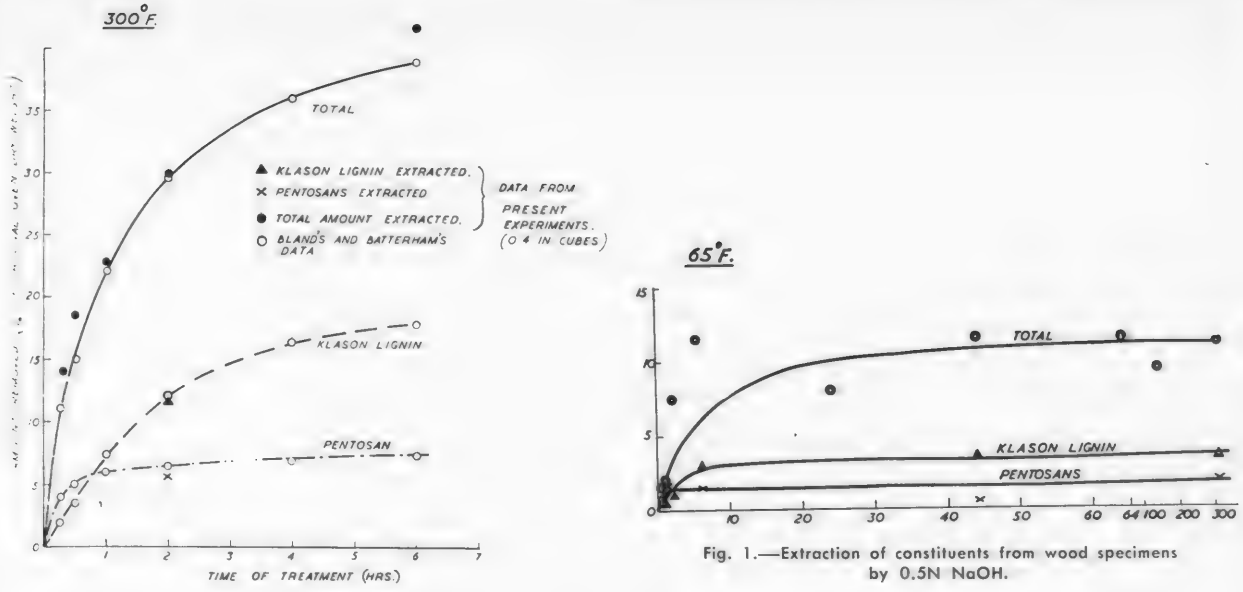

Fig. 1.—Extraction of constituents from wood specimens by 0.5N NaOH.

ments in sodium bicarbonate. Specimens were reconditioned, the radial shrinkage in some sodium chloride treated runs was significantly lower than in water treated controls, whereas recoveries were significantly lower after treatments in sodium bicarbonate. There was also evidence that the oven-dry weights of specimens treated in sodium bicarbonate decreased by as much as 10 percent during the immersion. Acidification with 0.0002N hydrochloric acid had no significant effect on shrinkage. Total shrinkages before reconditioning and collapse recoveries were, in general, several percent greater in sealed than in unsealed specimens, but this effect was only significant in the radial direction before reconditioning and in the tangential direction after reconditioning. Table 2 gives mean values of all specimens.

The normal shrinkage varied only slightly with different treatments. For instance, in *E. regnans* heartwood (Table 2), average normal shrinkages were 10.1 percent tangential (range 9.1 to 10.7) and 6.5 percent radial (range 5.9 to 6.8). Observed variations in total shrinkages are thus largely due to collapse.

Extraction with Sodium Hydroxide and Sodium Chlorite: Amounts of material extracted with sodium hydroxide (corrected for retention of NaOH) after various periods and estimations of Klason lignin and pentosans are plotted in Fig. 1, together with plots of experimental data obtained by Bland and Batterham (1) for extractions at 300°F. Unextracted material was found to contain 25 percent lignin and 15 percent pentosan.

Observations of total shrinkages and collapse recoveries after extraction with sodium hydroxide and sodium chlorite are summarized in Figs. 2 to 5. With increasing time of extraction, total shrinkages progressively increased to a maximum level, whereas recovery during reconditioning decreased to practically zero.

Discussion

Pretreatments of wood in inorganic salt solutions may be divided into (a) treatments that do not cause any appreciable change in the chemical composition of the wood substance, and (b) treatments that do cause such a change, either through extraction of constituents or by chemical reactions.

Treatments in sodium chloride and calcium chloride may be considered as in group (a), whereas the treatments in zinc chloride and sodium bicarbonate probably belong to group (b). The hydrolytic effect of 0.0002N hydrochloric acid is probably negligible, but concentrations of 0.01N or higher may be considered as group (b) treatments. Extraction with sodium hydroxide or sodium chlorite is, of course, also a group (b) treatment.

Tables 1 and 2 show, in general, no significant reduction in total shrinkage after treatments in group

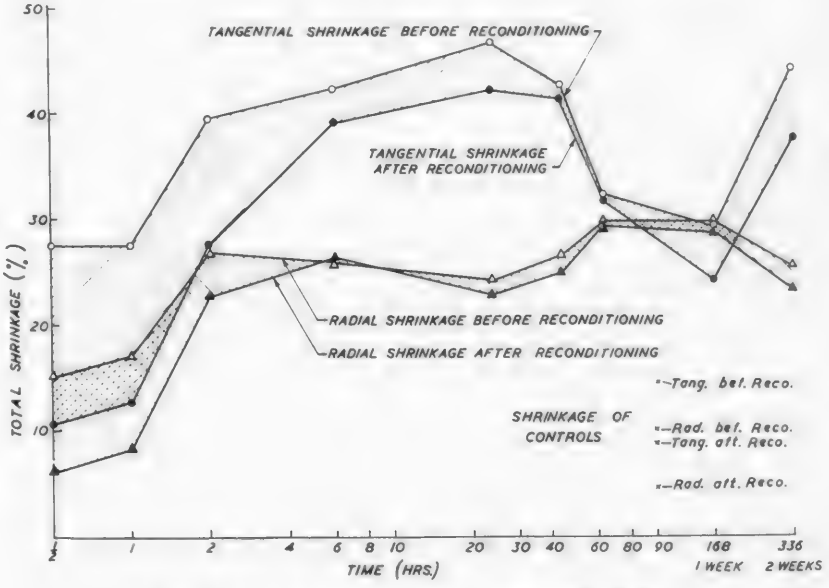

Fig. 2.—Total shrinkages and collapse recoveries after treatment in 0.5N NaOH at 65° F. (0.4 inch cubes).

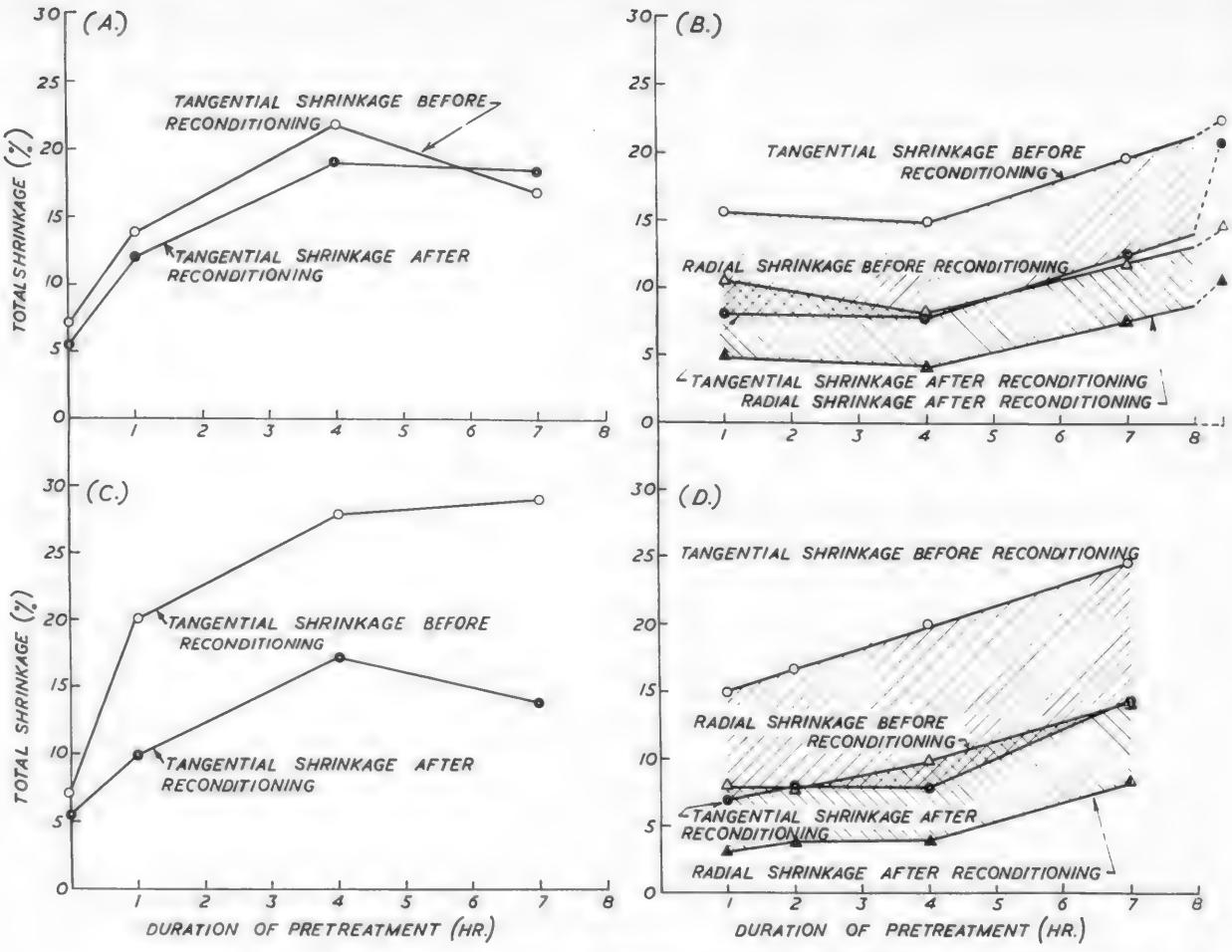

Fig. 4.—Total shrinkages and collapse recoveries after treatment at 158° F. in: A, 0.05N NaOH — 200 μ sections; B. 0.05N NaOH — 0.4 inch cubes; C, 0.1N NaOH — 200 μ sections; D, 0.1N NaOH — 0.4 inch cubes.

(a). As noted before, variations in total shrinkage are largely due to collapse. The slight reductions observed with the higher concentrations of sodium chloride may, however, be explained in part by the bulking effect of the salt (15).

After group (b) treatments, total shrinkage and hence collapse was in most cases significantly increased and recovery reduced.

On the other hand, Chudnoff (3) obtained considerable reductions in collapse after immersion of *E. camaldulensis* sapwood in zinc chloride solutions. Chudnoff encountered comparatively severe collapse in untreated sapwood control specimens, however, which suggests unusual properties of the material he used.

The extraction treatments with sodium hydroxide and sodium chlorite indicated an increase in collapse intensity and, at the same time, a decrease in recovery with progressive reduction in lignin and hemicellulose (*cf.* Fig. 1, 2, 3 and 5). Although a progressively greater uptake of sodium hydroxide through diffusion with increasing length of treatment may be expected in the 0.4 inch cubes, the results with microtome sections show that penetration effects could not be solely responsible for the progressive increase in total shrinkage. Weak concentrations of sodium hydroxide, which may be expected to extract only the more soluble hemicelluloses, increased collapse without appreciable effect on the shrinkage after reconditioning (see Fig. 4).

The hemicelluloses form a matrix supporting the cellulose framework of the cellwall, and are considerably more hygroscopic than either cellulose or lignin (2, 14). Their partial removal could thus result in greater total shrinkage, either as a simple displacement effect or by changing the stress distribution and strength properties within the cell wall during drying. Lignin is known to enhance the elasticity of the wood substance and to act as a reinforcement for the cellulose frame (17). Depletion of the lignin content should thus increase collapse and, in addition, reduce the ability of the wood to recover. On the other hand, the effects observed could also be due to the rupture of bonds between cell wall constituents by the chemicals used, or to reaction of these chemicals with the residual wood substance.

The present results thus do not yet permit an unequivocal interpretation of the observed behavior, but it appears that both lignin and hemicelluloses play an important part in determining collapse intensity, and that reconditioning recovery may be related to the presence of lignin.

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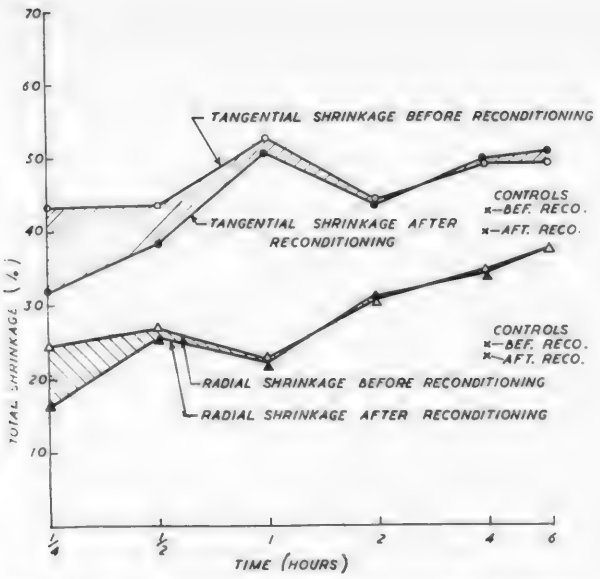

Fig. 3.—Total shrinkages and collapse recoveries after treatment in 0.5N NaOH at 300° F. (0.4 inch cubes).

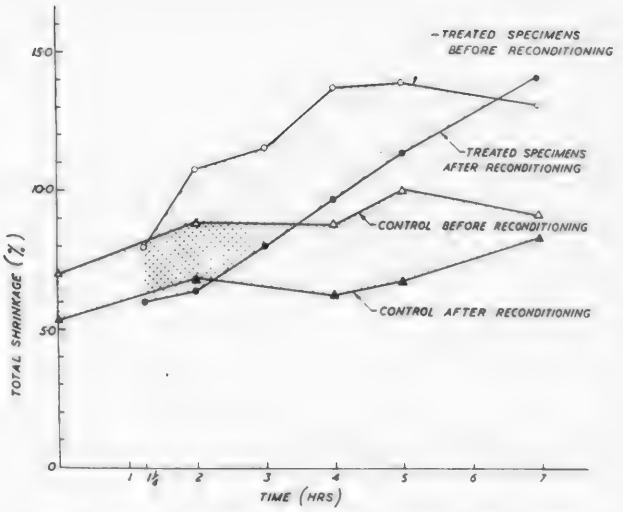

Fig. 5.—Total shrinkages and collapse recoveries after treatment in 0.25 percent $NaClO_2$ at 158° F. (200 μ sections).

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Building Codes:

THEIR RELATION TO FOREST PRODUCTS

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THE FOREST PRODUCTS INDUSTRIES are vitally interested in building codes, because, insofar as products of the forests find their market as components of building construction within urban areas, they are subject to influence and to possible, or actual, restraint by building codes and similar governmental by-laws.

To state this another way, it is a fact that the building official, backed up by his building code, can to an appreciable degree determine fully and finally

Building codes, to be beneficial, must be expertly interpreted and properly administered. They must provide safeguards, yet not restrict initiative in design, use of materials, or method of assembly.

much about the materials and the methods of their use as they go into buildings and structures. True, the building official is not the ultimate consumer, but nevertheless the effect can be much the same as having no market for certain forest products that cannot be sold for uses which are unlawful under the applicable building code.

On the other hand, it can be said that a good building code, properly administered, can be good for forest products markets by being liberal and thus an inducement to practical and

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economical construction with such products. In fact, a good building code is good for all construction materials. It is good for those who build, whether with their hands or their money. It gives order to the process of building and to the resulting community. Then again, a poor building code can be depressive not only to materials markets, but also to labor, to designers, to builders and definitely to the community.

Building codes as a subject is quite large. Much that is written and said about them is incorrect. It will be neither possible nor appropriate that more than a fast look at some of the principal elements be attempted on this occasion.

What is a Building Code?

The term "building code" generally means a codification of the local laws that regulate the construction, occupancy, and use of structures. Building codes include provisions for structural stability, and precautions for safety of persons and property from fire.

Many building codes contain provisions that regulate mechanical and other elements. In its strictest sense, "building code" means a codification of building by-laws that would include every law that regulates building construction and use. Some of the major subdivisions of such would be zoning laws, which designate the uses that may be made of land and buildings according to their location within the governmental jurisdiction; and housing laws (inclusive of slum clearance laws), which would have to do with the minimum standards for housing and which are in some respects social laws in that they closely relate to the welfare, health, and moral aspects of urban life. The building code invariably includes a designation of fire limits and further restricts construction within such limits. There are other regulations that are building laws, and these at times get all mixed up into one pot; at other times they are not only separated but administered by different authorities so as to overlap or even be contradictory.

Some are buried in state laws so securely as to be designated "hidden building codes". If they stayed hidden, they would concern no one. Often they are hidden best from the one who must ultimately foot the bill for compliance.

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Many jurisdictions have fire prevention laws, which serve a very important need and which should supplement the building laws but not overlap them.

Authority for Enforcing Building Codes

The authority of a building code is based upon the police power of the political government that has jurisdiction, whether it be a state, county, or municipality. Today, with our democratic way of life, the police power should not deprive an individual of rights or freedom of choice or action, except as such deprivation may be essential to protect the public peace, morals, health, safety or welfare. The building code under such police powers serves to safeguard life, health, and property in and about buildings.

To be enforceable under the police powers, a building code must be reasonable and certain. It must not be arbitrary, oppressive, nor discriminatory. Esthetic considerations alone are generally not supportable as building laws.

Historical Background

The building code is not a modern concoction. The history of building codes extends back for thousands of years. Such history, being neither dramatic nor romantic, is difficult to find. Historians did, however, record some of it. We find mention of building laws from the time of the ancient Babylonian Empire of Hammurabi about 2000 B. C., through Nero's Rome, into twelfth-century Europe, in England before the Great Fire of London, and in the Americas as soon as urban life provided the need. The more America becomes urban, the greater the need.

Historians did not clearly differentiate between building laws and building construction specifications. Even today there are those who think that the provisions of a building code should be so broad as to serve as specifications for esthetic and efficient structures.

A building code should not be as detailed as a construction specification. Building codes must permit the exercise of individual initiative in design, in the use of materials, and in method of assembly where the result is equally stable and safe as compared with the minimum standard of duty or performance needed.

It is the owner's responsibility through his architect, engineer or specifier, to so draw his contract, plans, and specifications as to result in the building he needs with due consideration for arrangement, rentability, maintenance, and insurability. These safeguards for the owner are not the responsibility of the building code.

While we are on the subject of specifications, it should be mentioned that there has been a lot of discussion within the last decade about building codes being performance rather than specification codes. Presumably those who say that a building code should not be a specification code have in mind the same thing stated above. This needs to be clarified further, however, because the courts will require that the code provisions, to be enforceable, be certain and specific, which is not too far from the word "specification". This, however, can be resolved if the statement of performance required meant a standard of duty required and that the details of how it be met, or the specification, only be recited as a way to meet the required performance. To assure this interpretation, most modern building codes now provide a procedure for the acceptance of alternate materials and methods of construction which accomplish the required standard of duty. A good building code will thus permit the use of materials or methods that comply with recognized standards developed through acceptable construction processes and by qualified agencies.

Providing Fire Safety

Building code stability provisions should go only far enough to assure reasonable precautions for the adequate strength and stability of the structure under the assumed use and loading. The fire precautions of a building code should be adequate, yet the minimum necessary: to provide time and means for the safe egress of occupants should fire occur; to confine a fire reasonably to the building, area, and story of its origin; and to give the fire fighting services ready access to and a chance to control the fire. Special occupancies and unusual conditions, of course, need extra precautions. Unfortunately, there are within many building codes restrictive provisions that fail to accomplish sufficient increased stability or fire safety to justify the difficulties and expense such provisions impose upon construction or its occupants.

Adequate fire precautions incorporated into a building however, are important for the successful control of fire, and such precautions are needed whether the materials of construction are combustible or non-combustible.

Many building codes do not adequately recognize the fire potential of contents, and over-emphasize the

o-called combustibility of the structural parts. The use of building materials that will not burn is not of itself guarantee of fire safety. For fire-safe onstruction, the proper use of materials and the overall arrangement of he building are of greater practical nportance than the selection of the uilding material to be used.

Some of the largest fires have occurred in industrial plants supposedly incombustible construction and using incombustible products. In any building codes it may be found hat unlimited heights and areas are llowed types of construction that are nsidered "fireproof", that is, where the structure—like a pot-bellied stove is non-combustible and to a degree re resistive. Unlike such stoves, fireesistive buildings are damaged by fires from contents, and the cost of repairing fire damage in these more costly buildings is appreciable. Some types of timber buildings are quite durable when subjected to fire, yet are often limited in size by building codes. Such codes discriminate against timber buildings.

Building Code Administration

No building code is complete without provisions for adequate administration and enforcement. Little is gained by a community that has laws regulating building construction where there are inadequate provisions for enforcement.

A building code can be administered effectively in the public interest—or it may be administered in a way harmful to the community. In many respects, a municipal building official with his codified building laws is like a cook with his cook book. A good cook can prepare a palatable and wholesome meal, regardless of the quality of his cook book, while a poor cook may fail to get the desired effect from even a good recipe.

A capable building official, when backed by the governing body of his municipality and supported by public opinion, can interpret and apply almost any code in a manner that is effective and beneficial to the public interest. A poor official or one who is unsure of himself because of lack of public support or political pressure can harm his ommunity substantially.

It should follow, then, that we are st as interested in good administran of building codes as in good codes. lany problems brought to our attenn are found to be due to misinterstation of a code rather than due to e code itself. If a building code were attempt to spell out every detail, it would fill many volumes. If it were of many volumes, its bulk and inertia would create more problems. To operate with a reasonably sized code text, there must be interpretations, and these must rest upon experience and good judgment.

Interpreting Building Codes—How Much Discretion?

The official charged with the administration of building laws has a tremendous responsibility. With responsibility must go authority. No matter how detailed the building code may be, he must to some extent exercise judgment in deciding compliance with the code. Some building officials know that they have considerable discretion and know the pitfalls; but many building officials strive for exact compliance with the letter of the law.

Some of this confusion as to the interpretation of building codes is because, although a building code is fundamentally a remedial law, that is, one intended to be construed liberally and beneficially to overcome the mischief that the legislative body intended be remedied, there are in most building codes several sections that list penalties, such as the statement that a violation of the code is a misdemeanor punishable by fine and/or imprisonment.

The presence of a few penalty provisions places the code in the shadow of a penal code that requires strict interpretation. It takes the wisdom of Solomon to navigate safely between the two, and many building officials take the safe route, at least for the early years of their term as a building official.

How does the building official get this wisdom of Solomon? There are several ways, such as years of experience with good public support, attendance at meetings with other building officials, and attendance at schools for building officials. All of which places a responsibility upon his superiors to see that the building official has the opportunity to get that wisdom and the backing to use his wisdom.

Most building codes provide help for the building official with respect to interpretation of his building code by creating for him a Board of Standards and Appeals, which can relieve him of some of the personal responsibility of code interpretation, particularly where there is much at stake.

A building official has quite a bit of authority. He can apply penalties that can be quite expensive to the builder. Besides the misdemeanor penalty already mentioned, he can issue stop orders, which can be very costly to a builder who has much labor and equipment employed. He can order completed work removed or even the complete demolition of a structure that is in violation of his code.

Building Code Adoptions and Revisions

It is probable that every municipality of any size within these United States has a building code of sorts in effect. Many counties have building codes and there are some state codes. Whether these are good codes or bad codes, the builders have to meet the requirements prescribed insofar as the applicable code is enforced. If it is not enforced, no one learns how bad it is. In fact, it may read so impressively that some other city may elect to copy it, not knowing the consequences.

The municipal building codes within this country may be roughly classified into five general categories as follows:

1) Codes that have been composed in a locality or copied from a locality code;

2) Codes that are copies of nationally recognized model building codes with few amendments;

3) Codes that are copies of nationally recognized model building codes but with extensive revisions and modification to suit local needs;

4) Codes that are prepared and sponsored by state governments;

5) Model or suggested code texts prepared by state municipal research bureaus or municipal associations.

It should be pointed out that certain regulatory documents or specifications, such as the Federal Housing Administration Minimum Property Standards, are not building codes because they are not enforced under the true police powers of the state. Such documents, although not within the scope of this discussion, can nevertheless have a great impact upon forest products markets.

Some of the reasons that municipalities adopt building codes are:

1) A good code can contribute materially to the orderly growth of a city, to the improvement of property values, and to the avoidance of slums;

2) The adoption of an accredited building code can be a factor in

getting the city a better classification for fire insurance rate purposes.

3) The Federal Government, in making Federal aid available for slum clearance and other housing purposes, considers the adequacy of the local building laws before the approval of grants;

4) Industries seeking sites for new plants consider the building code as it might apply to such a plant and to future plant expansion and as a safeguard to employee housing.

Some of the reasons for revision of building codes are:

1) The present code is out of print and needed revisions should be accomplished before an expensive new printing;

2) An existing code has become so patched up with amendments that an overhaul is needed;

3) The building code has become a political football and is revised as a campaign promise;

4) New materials or methods of construction appear to warrant code revision;

5) Some disaster has produced hysteria for more stringent laws;

6) A community decides to adopt a code that has uniformity with contiguous areas;

7) Communities using model codes adopt new editions as they are published;

8) Basic standards on which code requirements rest have changed.

Some methods of revising building codes are:

1) Assign the job to an already overworked building official;

2) Employ an expensive code consultant;

3) Adopt a model building code;

4) Adopt a state code or the code of another city;

5) Create a building code revision committee.

Since a local building code revision committee is often established for code revision regardless of the method used, a few words about such committees are in order. The committee that has the task of preparing, selecting or amending a local building code is usually composed of men who contribute their time and who have other occupations to absorb most of their attention. Though these committeemen may often represent professions and occupations identified with building construction, they may have had little prior occasion to become technically informed on all the specialized subjects involved or on the concept of safety that underlies building regulations. For these reasons these committeemen are inclined to rely heavily upon the information (or misinformation) available to them. Lacking good references, correct information, and competent help, these committees can get into trouble or the code revision can take many years. The forest products industries thus have the responsibility of bringing correct and sufficient information about their products to the attention of code revision committeemen as needed.

Some Concluding Observations

1) Building codes will constantly change through the years because the materials available for construction and the methods of construction change. Further, the attitudes of people change as to what building codes and housing codes should do, what constitutes reasonable safety within the limits tolerable to the public, and what constitutes public welfare. For example, it is unlikely that our early colonists ever heard of slum clearance, yet the Romans did. In fact, that has been cited as one reason why Nero is purported to have burned Rome. Today again we hear of slum clearance, or should we say "Urban Redevelopment"?

2) In the creation of building code regulations it should be kept in mind that the American people do not live in complete safety; rather they live a relatively safe life, considering the hazards that surround them. Absolute safety is not attainable. To reduce appreciably the few life casualties due to spread of fire in those buildings that conform with modern building codes, the construction and building use requirements would have to be so exacting, impractical, and uneconomical as to curtain needed construction. In fact, the requirements could be so restraining that the people affected might well prefer to be less safe with more freedom.

3) The few deaths that do result from spread of fire in buildings occur mainly in the older buildings that do not meet present-day safety standards. After a fire disaster, there may be public feeling for more preventive laws and as a result attempts are made to reduce fire casualties by imposing more and more restrictions in building codes. Since building codes mainly govern new buildings, they have little or no effect upon the buildings where the worst hazards exist. It is just such false remedies that cause the public to relax so that the "fire traps remain set" for future victims. Further, the resulting pyramiding of regulations applicable to new building tends as stated before, to depress construction, and thus markets for construction labor and materials. The need is not the propounding of more theory and more regulations for making buildings stable and firesafe, but rather through education, persuasion, and as much enforcement as possible the accomplishment of the safety precautions already required by good building codes.

4) Where building code regulations and restrictions aim at the ultimate conceivable instead of the minimum essential, they can surely defeat their objective. For example, overly exacting requirements for safety at such as homes for the aged can, because of cost and impracticability, forestall interim alterations that, if completed, could well reduce the existing fire hazards. Efforts should continually be directed towards obtaining reasonable standards and requirements properly weighted against the problems they create.

5) If a community has no building code or has a building code that has not been enforced, and it subsequently adopts a good code and enforces same, it may well increase construction costs —not lower them. On the other hand, where a restrictive building code or a reasonable code has been severely enforced, the adoption of a reasonable code and the accomplishment of proper administration thereof can reduce the cost of construction.

6) Finally, it should be realized that building code provisions, even for the model codes, are often worked out by small committees. Most of the committeemen are conscientious and competent. Regrettably, a few are crusaders, with prejudiced opinions, and some are not competent or are interested in personal or political aspects. Further, some, although conscientious themselves, are misled by those who would arbitrarily favor or handicap certain construction materials under a cloak of concern for safety or for modernization. Regardless of how a code revision committee is constituted, its decisions can have great impact upon building material markets. The forest products industries therefore have need to give ample attention to building code revision processes.

Measuring Machine Capabilities[1]

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Machine capability studies put a numerical value on variability as a basis for improving quality and recognizing variability that can be reduced. Methods compared are $\bar{X}$ and R chart, Multi-Vary Chart, and Span Plan Process Capability Analysis.

LET US DEFINE what is meant by measurement of machine capabilities. We mean the analysis of the output of a machine to determine its natural or inherent variability. All processes and machines have a certain degree of variability because of variation of raw material, inability of machines to reproduce each operating cycle exactly on successive parts, machine wear, and so forth.

The essence of machine capability studies is that we place a number on this variability, in order to lay the basic groundwork for an improvement in the quality. It also helps us recognize the portion of the total variability that can be reduced feasibly.

A machine capability study may be undertaken for anyone of several interrelated reasons:

1. To reduce or eliminate scrap or rework, or sorting operations following a certain machine operation.
2. To determine on which machine a certain critical operation should be run.
3. To give the Engineering Department an idea of what the machines can do in the way of holding tolerances to enable them to set better tolerances.
4. To determine whether to buy or demand improvement in machines to be purchased, based on the capability of the machine.
5. To discover machines that require maintenance, overhaul, or that should be replaced.
6. To enable Engineering to choose between alternate methods of production.

To attempt to control or improve the quality of any operation demands precise, factual knowledge of that operation. A basic portion of these facts lies in the realm of machine capabilities. Knowledge and use of machine capability information means dollar savings in scrap, rework, and other wasteful costs.

[1] Presented at Session XVI, Quality Control, FPRS 14th National Meeting, June 5–9, 1960, Montreal, Canada.

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Measuring Tools

In general, a measuring tool must be refined enough to divide the tolerance range into at least 15 units of measurement. For most woodworking operations, this will mean an instrument capable of measuring to the nearest one thousandth of an inch. For example, if the tolerance range is plus or minus 1/64 inch, the situation could be portrayed as shown in Fig. 1.

In this case the tolerance range is divided into approximately 32 equal spaces. This is an ideal situation.

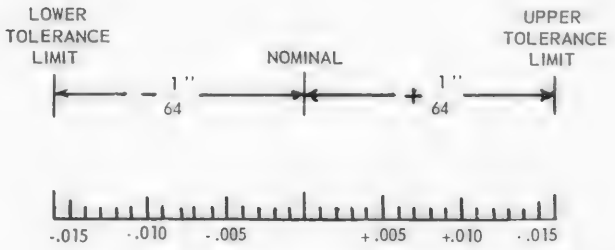

Fig. 1.—Deviation from nominal in 0.001 inch units.

Basic Statistical Properties That Must be Evaluated

Any methods used must be determined by their ability to evaluate four basic statistical properties of every process:

1. The centering or aim of the process in relation to the tolerance limits.
2. The spread or total variability of parts produced by the machine over an extended period of time.
3. The capability or inherent or natural variability that exists among successive pieces produced.
4. The stability of the process or the extent to which time affects the centering and capability of the process.

Techniques That May be Used

In general, the choice of techniques to be used depends primarily on complexity of the process. Three of these techniques are:

1. $\bar{X}$ and R charts
2. Multi-vary charts.
3. Span Plan method of process capability analysis (1)[2].

In general, the $\bar{X}$ and R chart and multi-vary chart methods would be used on simpler problems, and the Span plan technique on the more difficult and complex problems.

In the rest of this presentation, it is assumed that the reader is acquainted with various common statistical measures and terms and techniques such as average, range, standard deviation, normal distribution, and $\bar{X}$ and R charts.

[2] Numbers in parenthese refer to the literature Cited at the end of this paper.

Measurement of Simple Machine Capability

$\bar{X}$ and R Charts, Frequency Distribution, and Normal Probability Graph Paper: With reference to the "Basic Statistical Properties" mentioned previously, four aspects of the machine process must be identified and evaluated: the centering; the total spread; the capability; and the stability. All possible variability must be accounted for in the sample so as to determine the above aspects of the process. In order to do this, the following procedure could be set up and appropriate analyses made:

1. Ten samples of 5 parts each could be drawn from 4 different lots made at different times. Each sample of 5 should be of consecutively produced pieces, and the 10 samples from each lot should be taken at random times covering the entire period of production of one lot.

2. The ten samples for each lot are plotted on an $\bar{X}$ and R chart with tolerance limits and control limits also plotted on each chart. If more than zero in 25 or one in 35 points are outside the control limits, the process is considered unstable. This means that a change takes place in the process during a period of time. This is a valuable clue that the process is not in statistical control and that there are assignable causes at work. The process is not stable. From the data from all samples, $\bar{R}$ is calculated. Then the quantity $6\bar{R}$ divided by d_2 is calculated. This quantity is the capability of the process.

To determine the centering, the grand average $\bar{\bar{X}}$ is calculated from all the data. This tells how well the process is centered between the tolerance limits.

3. A frequency distribution is made of all measurements taken from all samples. From the frequency distribution, the standard deviation is calculated in the usual fashion. $\bar{\bar{X}} \pm 3\sigma$ is the spread of the process, and includes all types and sources of variability.

4. If the process is unstable, then the spread will be larger than the capability. This indicates that the process could be improved by the location and removal of the assignable causes, whatever they may be. Stability is actually a measure of the time to time variability present in the process. Examination of the two sample $\bar{X}$ and R charts in Fig. 2 will illustrate very quickly a stable and an unstable process.

Obviously, the process in the left-hand chart is stable. The right-hand chart gives a very clear picture of instability. It also gives a pretty good idea of where to look for causes of this excessive time to time variability.

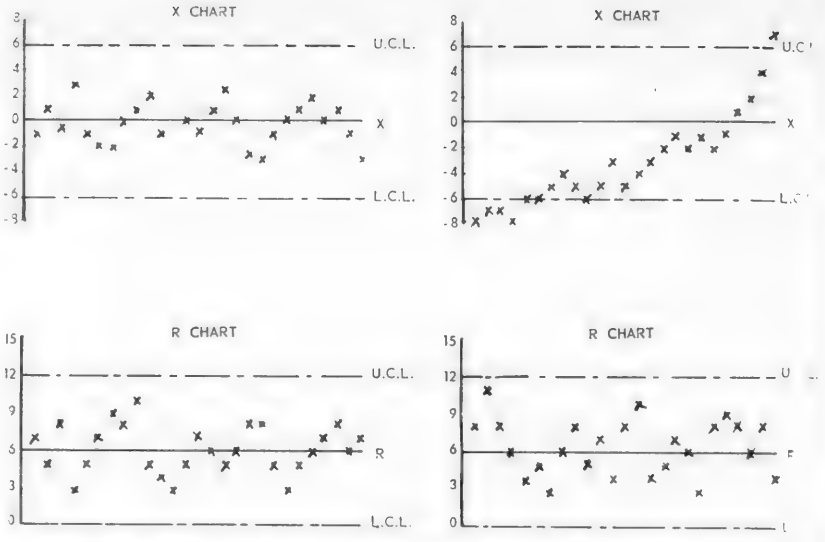

Fig. 2.—Analyzing machine capability by means of $\bar{X}$ and R charts.

If the process is stable, then the capability will be statistically identical to the spread, and we may conclude that:

1. The process is in statistical control.
2. The only way to improve quality is to change the process. That is, buy a new machine or process in a different manner, for instance.

Graphically, the following situations could exist (Fig. 3) in a machine capability study with a stable process when process spread equals process capability.

1. a. $\bar{X}$ indicates the centering is good.
   b. Capability is good since we are well within tolerance limits.
   c. Process is in good shape.
2. a. $\bar{X}$ location shows centering is off, should be recentered.
   b. Capability is good.
   c. Process can be made to operate within tolerance limits by shifting the aim.
3. a. $\bar{X}$ position indicates centering is good.
   b. Capability is inadequate.

If a process is unstable, so that spread is larger than capability and points are out of control on the $\bar{X}$ and R control chart, the following typical situations could prevail (Fig. 4):

1a. Centering is good.
   b. Spread is smaller than tolerance range. No action is required, although the process could be improved if need be.
2a. Centering is good.
   b. Spread is larger than tolerance range, capability is smaller than spread. Process is unstable - locate assignable causes of instability, if economically feasible, and remove.
3a. Centering is good.
   b. Spread and capability both exceed specifications.
   c. Process must be changed or tolerance limits broadened.

In using the $\bar{X}$ and R chart in the analysis of machine or process capability, certain somewhat limiting assumptions have been made about any machine or process being studied. Their effect will not be of significant importance in most work of this type, but in some cases it may be important. Some of these limitations are given in the following material.

a. It has been assumed that the study will pick up any long-term effects of time on the process. That is, the data were taken over a long enough period of time to reveal any significant time-dependent contributions to variability of the process.

b. It has been assumed that all of the product goes through the same machine, the one that has been studied. If this is not the case, a similar analysis would have to be made of product from each machine.

c. It has been assumed that the relative contribution of error of measurement is insignificant.

d. It has been assumed that the single measurement taken on each piece accurately represents the value of the measured quality characteristic for that piece. If the position at which the measurement was made has a significant effect on the measurements,

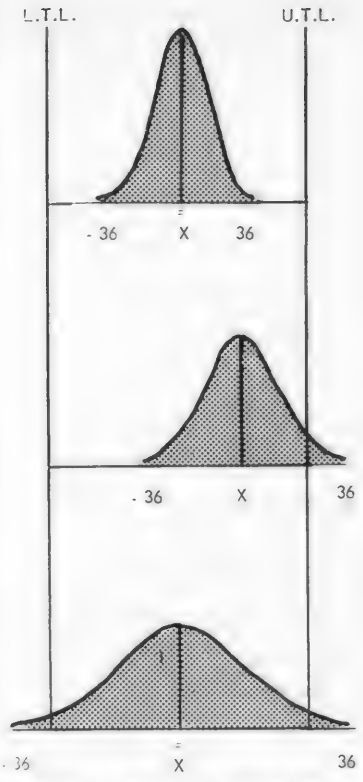

Fig. 3.—Examples in which spread equals capability.

analysis will not be complete until this variability has been measured.

e. Assumption of normality. It has been assumed that the distribution of the variable measurements concerned is normal. Only in the normal distribution will $\bar{X}$ plus or minus three standard deviations encompass 99.73 per cent of the measurements.

If, because of the appearance of the histogram of all measurements a question arises as to whether this distribution is normal, there are two well-known ways in which to test the distribution for normality. They are by using normal probability graph paper, and by using the X^2 (Chi squared) technique. The first is relatively quick and easy, but not as precise as the second.

1. Normal probability graph paper (2). This type of graph paper can be purchased from several companies. In plotting the data, it is the best practice to use the original measurements and not some coded form of them. General rules for plotting are as follows:

a. Arrange the values in ascending order of magnitude.

b. Mark graph paper with actual measurements on the vertical axis (Arithmetic scale) and the percentage values on the horizontal axis.

c. The ith value is plotted at a point equal to its actual position on the vertical axis, and at a point equal to $i + 1$ on a horizontal axis. For example, the value 1.005, which is 10th in rank on a sample of 99 is plotted at 1.005 and $\frac{10}{99+1} = .10$ on the horizontal axis. Determine the position of the points in the bottom half of the data up to the 50 percentile line and then start at the top and work back to the middle again. This may cause a small amount of overlapping, but in the normal distribution it is insignificant.

d. A straight line may be fitted to the data by holding a clear straight edge at the lowest point and swinging the edge until it bisects the far half of the data (that is, the points above the 50 percentile line). Then reverse the procedure, starting from where the straight edge lay at the top of the chart and bisect the lower half of the data. Do this until the straight edge and the 50 percentile vertical line divide the chart into four quandrants, each with the same number of points. Then draw a straight line through the data.

e. If the straight line seems to be a good fit, the distribution is normal. The relative goodness of fit can be tested with the following simple tests.

Count the number of runs observed above and below the line of best fit (a run is a sequence of two or more consecutive points on one side of the line). If the total number of runs above and below the line is less than $\frac{n}{2} + 1 - \sqrt{n - 1}$, or if the longest run contains less than 8 points one can be fairly sure that the data do not conform to the normal distribution. If this is the case, it is time to shout for help from a first-class statistician.

2. X^2 test for goodness of fit. This technique would only be used in a case of extreme importance where the results of the study might be critical as far as a decision involving a large sum of money is concerned. In most cases where there is a doubt as to the normality of the distribution of data, method No. 1 will suffice. Space precludes detailing exactly how the X^2 test is made. However, the texts numbered 3 and 4 in the bibliography explain in detail how X^2 is calculated and interpreted.

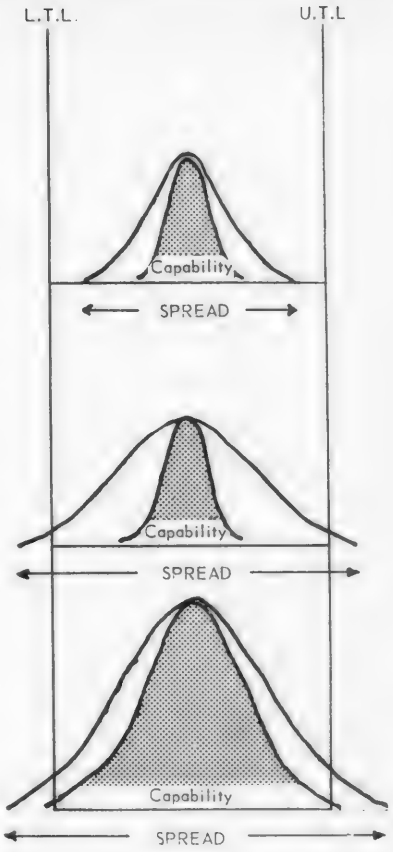

Fig. 4—Examples in which capability does not equal spread.

Analysis of Machine Capability With Multi-Vary Charts

The multi-vary chart method of capability analysis is primarily a non-quantitative technique, wherein one can visually analyze the process.

With this technique, the analyst, by making the proper measurements, can study the relative contribution made by within-piece variability, piece to piece variability, time to time variability, and machine to machine variability. The basic procedures are as follows:

1. Several samples of five consecutive pieces are taken from the process over a period of time. Two or more measurements are made on each piece, depending on the part so as to determine variability within the piece.

2. The measurements from each piece are plotted on a chart with the tolerance limits shown on the chart. One vertical line is drawn for the measurements on each piece connecting the lowest and highest measurements. If there are several machines to be studied, all machines and their samples should be shown on the same chart to make it easier to interpret.

3. The chart may be visually interpreted as shown in Fig. 5.

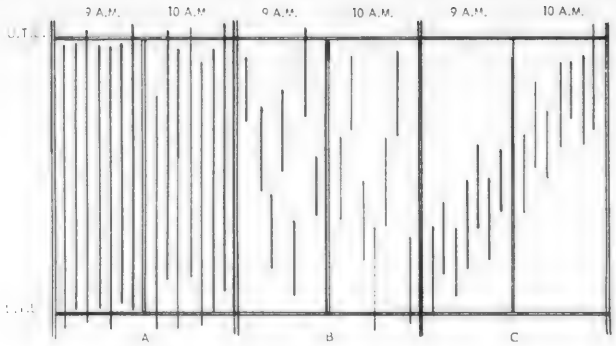

Fig. 5.—Three typical examples of a Multi-Vary chart capability analysis.

a. Case A in Fig. 5 is obviously a condition where within-piece variability is very important. This is obvious because the length of vertical lines is almost equal to the entire tolerance range. In general, if the average length of the vertical line amounts to more than $1/2$ of the tolerance range, then the most fruitful place to work to reduce total variability will be on within-piece variability. Usually this means work tool alignment, squareness, and so forth, will have to be improved.

b. Case B shows a case of the machine that is unable to reproduce its work cycle in the same manner from piece to piece. This is obvious because, while within piece variability is small as shown by the length of the individual lines, the consecutive lines jump all over within any given sample. Some factors to look for in this case may be lose clamping or gauging fixtures, insufficient rigidity, excessive clearance in bearings, and so forth.

c. Case C is clear case of the influence of time to time variation. This is easily seen because of the trend from sample to sample. To reduce this type of variability, one should examine such factors as tool wear, lot to lot difference in material, and so forth. From this brief discussion of multi-vary charts, we can see it is a simple but effective technique for isolating the important sources of variation among several possibilities.

The Span Plan Technique

The Span Plan technique was developed by Leonard A. Seeder and David A. Cowan (1). This technique si essentially the use of analysis of variance to study quite precisely the different components that make up the total variance of a process. Analysis of variance techniques are commonly applied to experimental design problems. The Span Plan applies analysis of variance to the dissection of machine variability by means of a fixed series of steps, sampling rules, precalculated conversion factors, and decision rules, which result in a very clear-cut analysis procedure that will give the information needed to make good decisions about machine capabilities. It is adequate for use in the most complex situations that any quality control man is likely to find himself. It is based on a general method of attack that will fit any type of problem.

The explanation of this technique will not go into all the detail of computation. It will explain in general the logic and generalized steps the analysis follows—those interested in actually using the technique in their own work should purchase, Literature Citation (1) from the American Society for Quality Control.

Fig. 6 will help visualize what is included in the total spread of a process. Each of the trapezoids in Fig. 6 represents a single piece or unit. It is shaped as a trapezoid instead of a rectangle to give the idea of variability within a piece—positional variability as seen in Fig. 6. In Fig. 6 there are three streams that merge to form lots of finished product, with the pieces from each stream mixed randomly with the pieces from other streams.

Measurements, if taken at the same position on successive pieces, would show piece to piece variability. (See center stream in Fig. 6). This variability is made up of inherent variability plus error of measurement due to the measuring instrument. Measurements taken at random positions on a piece would differ from the measurements taken at the same position, and this would give a measure of piece positional variation. The total of inherent, error of measurement, and piece positional variabilities would give within—time variability. That is, it is the amount of variability measured within a very short period of time.

Measurements taken periodically in samples collected (as in the top stream in Fig. 6) would vary from one to other because of the time to time variability within the stream. The sum of the time to time and within-time variabilities equals within-stream variability.

The next highest stage is the stream variability, which will, of course, have a larger total spread than the within stream variability. Lastly, the sum of within-stream and stream to stream variability is within-lot variability. The final total variability or total spread will be the sum of the lot to lot variability and within-lot variability.

Now refer to Fig. 7, which shows the five stages of the complete span plan analysis. The general procedure for each stage is given below.

Stage 1. Sample a number of lots of finished product and determine the sample, lot to lot variability, within-lot variability, and then sum to get the total span. If the total span meets the tolerance limits or can be re-aimed

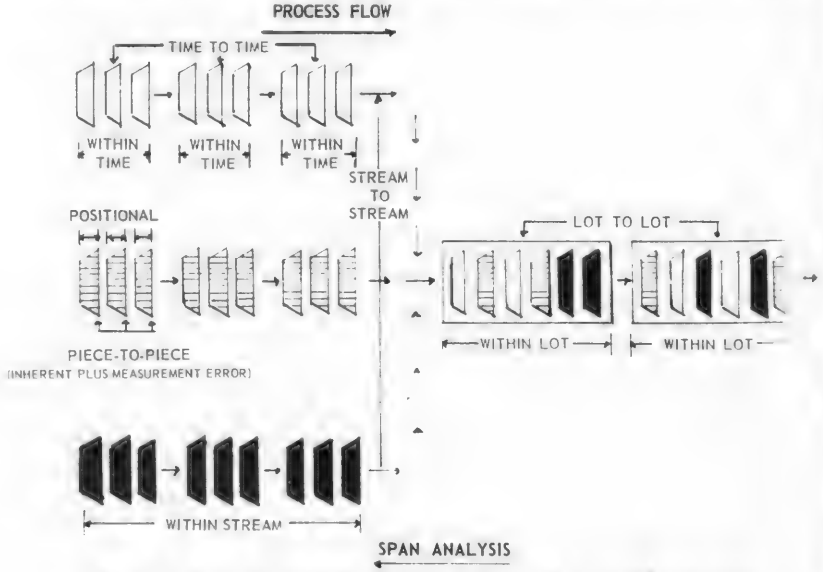

Fig. 6.—A generalized example showing the meaning of the different types of variability dissected by the Span Plan.

› do so, go no further. If the total pan cannot meet the tolerance limits, o to Stage 2.

Stage 2. Again sample the process › as to obtain the stream to stream ıriability as components of the with-ı-lot span. With the stream to stream ıriability isolated, it can be deter-ıined whether it is a major factor that eeds further work to get the streams ıore alike.

Stage 3. If the within-lot span is ill too large to meet the require-ıents, again sample the process in ıch a way as to measure time to time ıd within-time variablities. This is ıone by selecting one stream and tak-ıg samples of consecutive pieces over ı period of time. This breaks down he within-stream span to time to time ıd within-time variabilities. If the ıme to time variability is large, inves-ıigate further. If the process still will ıot meet requirements, go to stage 4.

Stage 4. Sample again to break down the within-time span into piece to piece and piece-positional variabili-ties. If necessary, go to stage 5.

Stage 5. Finally, break down the piece to piece span into error of meas-urement and inherent variability.

This is as far as it is possible to go in dissecting machine variability.

This brief overview of the Span Plan technique has been given to show some of the procedures involved, and the logical steps that are taken. The actual mathematical procedures in-volved in making the determination of the meaning and significance of the re-sults at each stage is done through analysis of variance techniques and certain rules of significance, mathe-matically stated.

Conclusions and Review

To this discussion of the methods of analyzing machine capabilities, let us look at the advantages and disad-vantages of each method in turn.

$\bar{X}$ and R Chart Method:

1. Advantages
   a. It gives the most accurate value for centering or aim of the process.
   b. By taking the sample values one can compute the standard deviation and arrive at the spread of the process.
   c. Capability is objectively meas-ured by $\frac{6\bar{R}}{d_2}$
   d. The control limits for $\bar{X}$ and R give an objective measure of the stability of the process.
   e. It is familiar to most people in the quality control field.
   f. Gives consistency of interpre-tation by different individuals.
2. Disadvantages of $\bar{X}$ and R chart method
   a. It is not easy to explain to others not familiar with statis-tical principles.
   b. It is not as powerful or gen-eral a technique as the Span Plan.
   c. The technique is not able to analyze for different streams of product or to show piece position, error of measure-ment, or long-term time con-tributions to the total vari-ability.

Multi-Vary Chart Method:

1. Advantages
   a. Visual inspection of the length of the vertical lines give a rough measure of with-in-piece (piece-positional) variability.
   b. Visual inspection of the rela-tive positions of each vertical line gives an idea of the ap-proximate centering of the process.
   c. Visual inspection of the posi-tion of the succeeding sam-ples gives an idea of long-term time trends (time to time variability), if the pe-riod covered is long enough.
   d. Visual inspection of the scat-ter among successive lines in each sample will give an idea of the capability.
   e. It is very easy to explain and interpret to others who may not be familiar with statistical principles.
2. Disadvantages
   a. Not precise enough because there are no mathematical rules developed.
   b. Different observers may reach different conclusions.
   c. One cannot segregate error of measurement, stream to stream, and piece to piece variabilities unless specialized sampling plans are developed.

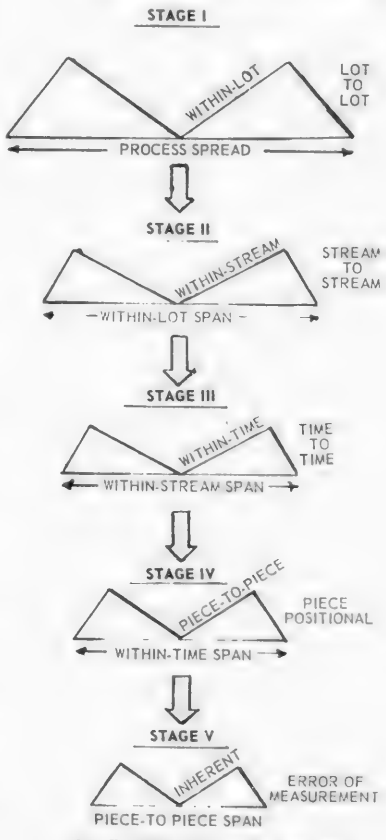

Fig. 7.—The five stages of the Span Plan analysis.

Span Plan Method:

1. Advantages
   a. The Span Plan can be applied to all processes, no matter how complex.
   b. A minimum of preplanning, designing of sampling tech-niques, and so forth is re-quired.
   c. A high level of precision and ease of interpretation is in-herent.
   d. Different investigators will reach identical conclusions because the decision rules are preplanned in terms of actual numbers.
   e. The Span Plan forces concen-tration on only those factors which contribute most sign-ificantly to the variability.
   f. All the different types of vari-ability can be measured.
   g. The centering, spread, cap-ability and stability are pre-cisely measured in the analysis.
2. Disadvantages
   a. Each of the steps must be done in order through all the sub-steps before one can move to the next stage, which means a small loss in flexi-bility.
   b. It may be somewhat difficult to explain, although the re-sults when expressed as in the pictogram form in Fig. 6 are not difficult to understand.
   c. It must be assumed the nor-mal distribution law holds throughout the process.

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Let's Face Our Problems[1]

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Woodstock, Ontario

IN THE 1920's, were you in the lumber or veneer business in the Ontario hardwood region, you would have found the following:

1. Sawmill labor was paid 15¢ to 45¢ per hour.
2. 4/4 F.A.S. birch sold for $75.-00 per M/F.O.B. Mill.
3. Birch stumpage sold for $1.00 to $1.50 per M.
4. Winter log hauls and spring drive were common in the North, railroad logging was common further South.
5. Most mills were driven from central line shafts.
6. Unions were not found in the lumber industry.
7. Provincial and federal taxes were comparatively insignificant.
8. Social security, unemployment insurance, and pension programs were virtually unknown.
9. Safety programs were of secondary importance.
10. The operation of business was simple and direct.

Contrast the above with today:

1. Sawmill labor in Ontario is paid $1.15 to $2.00 per hour.
2. 4/4 F.A.S. birch sells for $290.-00/M F.O.B. Mill.
3. Birch stumpage sells for $12.00 to $15.00 per M.
4. Year-around truck hauling is replaced the sleigh haul, the drive and railroad logging.
5. Practically all mills built today have individual motor drives.
6. Union organization is very common.
7. Provincial and federal taxes are very sizable, siphoning off approximately one-half of the profits.
8. Social security, unemployment insurance, and pension plans are with us to stay.
9. Safety work is a very important phase of every industrial plant's program.
10. Business, with is many new facets, has become a tremendously complicated thing.

A stimulating discussion of how to face major problems in the manufacture of lumber and plywood brought on by rapid changes in the economic climate during the last 3 decades.

These contrasts, which have developed in the last three decades, are evidence of the evolution that is taking place in the logging, sawmill and plywood businesses. We are faced with conditions today that would have made the rugged individualist of 30 years ago throw up his hands in despair.

These situations, these problems with which we are confronted today, are probably the best thing that could have happened to the wood industry. We can no longer figure to "cream log" and run. We cannot afford extravagant and wasteful methods. We are getting concerned—we are throwing off our lethargy. We are beginning to think because we have become aware of the fact that, unless we find better methods and equipment, we a headed for economic oblivion.

Until comparatively recently, t fact that we only used one-half the log that we brought in from t woods in either the sawmill or t plywood plant was not particula alarming. If an area was cut out th was another area to move to. Wh sawmilling was a relatively simple o eration, grades were easy to learn. L bor, without the present cars a highways, was not as mobile as toda Why worry about labor! Today in the lumber and plywood indust are competing with mining a smelter plants, with auto and aircra with civil service, and with many ot ers for both labor and professiona help. It is no longer a question f us to arbitrarily determine what w can afford to pay. We are confronte with a situation in which we are goin to have to bid for labor on a relativel open market. We are going to hav to bid for "brains and leadership" talent with industries who are well aware that, with the increase in problems in running a business today over those of 30 years ago, they cannot leave the selection and training of leaders to chance.

We can't shrug our shoulders and say "all right, we pay the extra cost for material, for labor, for supplies.— we'll pass it on to our customers". We have lost many markets as it is. If we get careless we can lose ma y more. There are few instances wh re the peculiar properties of wood ma e it an indispensable material. There re many competitors for forest prod ts markets, in addition to the comp i-tion of foreign lumber and plywo d. Manufacturers of moulded fiber pr d-ucts and panels, steel, brass, alumin m alloys, vegetable fibers, masonry pr d-ucts, will jump in and seize a part r all of markets controlled by for st products if we pass these increa es in costs on to customers.

The fact that wages are higher a d going higher, if we can read the han d-

[1] Presented at Session X, Lumber Manufacturing, FPRS 14th National Meeting, June 5–9, 1960, in Montreal.

The Author: George French is a graduate of the New York State College of Forestry with BS and MF degrees. He also attended the New York University of Engineering.

riting on the wall, does not mean at the labor costs per unit of production should go up. The fact that the uality of logs is going down does not ean that the quality of our production should go down. The fact that e're going further for logs and that e are shipping our finished products rther does not mean that the cost of ansportation should go up. What it es mean is that we have got to take f our coats, roll up our sleeves, clean f our glasses, dust off our brain cells d get down to work. We have got to velop some cold, hard-headed busi- ss answers.

. We have a disease in America today. We are looking for easy answers. We want the government, we want the associations, to do our work. We want subsidies, high tariffs, crutches of any sort. We have got to learn in this new business environment to stand on our feet as an industry and to work together to the degree that is necessary to grow and develop.

It is my opinion, after over 35 years of work in the engineering, operating, construction and management phases of auto body, furniture, logging, sawmilling and plywood manufacture in both hardwood and softwood fields, that our answers are going to come from one thing only, and that is infinite attention to detail. No detail is too small to avoid scrutiny, no practice so sacred as to avoid questioning, no course of action so obvious but what it should be examined. Once we understand the machine, the method, the technique, we should determine first if it is necessary at all. If it is, then can it be done in a better, more economical manner? We do many things in our business that don't stand up as sound business under critical examination. When we do find improvement is possible, then we must have the courage to execute our solutions.

The life of a successful business is contingent upon the ability of that business to make a reasonable profit. Many interests and people are dependent upon this ability of a business to make a profit. Ownership is dependent on it, of course. Those who make their living in business are dependent upon it. The government of our countries is dependent upon profitable business. Transportation systems, communication systems, local communities—all are dependent on stable, profitable business. An industry that is not profitable is a sick industry, it hurts all of those it touches. Unless the situation that makes it unprofitable can be corrected, it will die. A profitable industry will attract good personnel; it will attract capital; it will stabilize national and community life. It is a good thing.

This profit is basically the difference between cost of sales and sales. Sales is an important part of this picture. Much could be said about it. It does not fall within the scope of this discussion other than to state that, unless the products produced appeal to a customer, any effort spent in improving methods of manufacture and reducing costs is wasted effort.

Costs naturally are broken down into four categories: 1) material, 2) labor, 3) load or burden, and 4) selling and shipping expense. Let's spend a little time in examining them:

Raw Material

The raw material of the sawmill and plywood or veneer plant is the log. The variations in logs are infinite. There are characteristic variations due to species. There are variations due to age, to the site on which it grew, to knots, to rot, to forest fire damage, to insect infestation, to stain. These might be classified as natural influences on the character of a log. The instant a man puts an axe or a saw into a tree he begins to influence the character of a log. Supposing we follow a bucker and faller into the woods. He must start using judgment immediately. Should he fell the tree or should he leave it standing? If it looks unsound, if "conk" shows, if the grain is too crooked, if it is hollow, perhaps he should leave it. How defective it can be and still warrant cutting will depend on the market, the cost of logging and hauling, whether the sawmill or plywood furnishes raw material in the form of chips to a paper mill. Before the tree is felled these decisions have to be made. Once the tree has been felled with a minimum of breakage, a whole new series of decisions have to be made. Is it a peeler, a veneer log, or should it go to the sawmill? These decisions are important, for veneer log lengths differ from sawmill log lengths. Even after the decision has been made to send it, for purposes of this illustration, to the sawmill, he has got to cut it into the best lengths possible for the mill. Ten foot logs are undesirable in many mills. A 20-foot log should be cut into an 8 and a 12 foot length, a 22-foot log into an 8 foot and a 14 foot log, and so on. These lengths also will be influenced by the character of defects present. For example, an otherwise sound 16 foot log, 12 inches in diameter, with a 6 inch sweep in it, will produce 40 percent more lumber and of higher grade if it is cut into two 8 foot logs.

Not over 50 percent of the wood fiber brought in from the woods in the form of logs is shipped from the sawmill in the form of lumber or from the plywood plant in the form of plywood. Logging practice can contribute materially to this loss. Correlation of logging and conversion plant practice must be close. The wood departments have got to deliver more and more material from a given stand in the woods to the conversion unit in a form that can be converted profitably into salable products. This does not mean dumping "junk" on the conversion unit. It calls for the closest type of cooperation between the woods and the mill.

There are, of course, many logging costs and practices in the wood that are of no concern to the mill except as they influence the cost of logs to the mill. The advent of the power saw, of year-around truck logging, of improved log-handling equipment, of the bulldozer and cat, have wrought many changes in logging. Unquestionably the most frustrating, but still the most important, phase of logging, is to get more of the stand to the mill in a form that can be profitably utilized. This is the big problem in logging.

Much of the blame for wasteful practices and poor utilization of raw material can be laid directly to the conversion units. There are many reasons for this. Certainly one of the reasons is emphasis on the wrong goal. The common salutation in the sawmill world is "What production are you getting?". The emphasis is on production. Good production is essential in a mill. It is significant, however, only when it is coupled with yield or volume recovery commonly spoken of as over-run, and the grade yield or quality recovery tied in with the production per man hour.

Let me illustrate a few situations in the sawmills that are quite common:

1. No sawmill operator likes to produce scant lumber. To play safe, it is not unusual for a mill to cut lumber $\frac{1}{16}$ inch full to take care of this condition and avoid customer complaints or expensive sorting techniques. Normally there is some reason for scant lumber. It may be the carriage set works, the carriage tracks, the saw tension, the saw guide, half-frozen logs, or some other reason. Rather than isolate the cause and eliminate it, we cut the lumber $\frac{1}{16}$ inch full and cover up. Let's see what the decision costs. Suppose we are cutting birch, producing 4/4 at an average value of $100.00 per M at the rate of 20M per day, for a year of 240 days. We have lost 6 percent in volume. At no extra labor cost or log cost we could have increased our sales recovery on an annual basis of $28,000, had we found the real cause and corrected it.

2. Another big cause of reduced profits in a sawmill is failure "to go for quality". There are many schools of thought on how to saw lumber. I don't propose to enter the argument. As long as the end results are correct I don't care which school is followed. That first cut in the log is very important. It determines to a large degree whether we limit our defects to one or two faces, in many cases, and whether we get the maximum amount of high-grade lumber. The general rule for developing grade is: turn a log whenever by so doing you can get a higher grade board. The reason for this is obvious.

Another basic fact relative to logs is that the high-grade material lies in a band parallel to the bark. This is not a new observation; it has been known for years. Carefully controlled studies in Canada of birch logs with veneer logs removed and in Appalachian hardwoods have shown that, where logs were cut with the slab cuts parallel to the bark, that is, taper sawn, increases in sales value of lumber produced amounted to 25 percent and that overrun was not adversely affected. Again going back to the birch mill producing 20M per day and not taper sawing, with a sales value of $100.00 per M., taper sawing would have improved the profit picture $500 per day or $12,000 per year. Unless one is well equipped for taper sawing, a reduction in production could nullify this gain. The profit potential is there. The method of equipping the mill is a problem for each mill to sweat out. We cannot afford to make wedges to true up a tapered log with our highest grade material. We should make wedges out of $40.00 material, not $300.00 material.

Thoughtful analysis will bring out additional fields of study not only in log break down but in edger and trim work as well.

Futhermore, as soon as we make a piece of lumber, we start to pull its grade down. If we stack it in the yard we are careless in protecting the ends. We allow rain to beat in on it. We leave the top layer exposed to sun because we are going to add another course tomorrow. I have seen 150 bd. ft. of bright, clear F.A.S. surface checked seriously because yard men failed to protect it. Poor pile foundations, poor sticking practices, poor pile covers, all contribute their influence in reducing profits.

Two observations stand out in considering the sawmill industry, and they are just as glaringly apparent in the veneer and plywood industry:

1. There is a surprising unawareness of where our profits have disappeared.
2. We as an industry are not set up with adequate "measuring sticks" or controls to evaluate improvements. We get lost in a maze of wishful thinking, in half-hearted developments. We get discouraged. We give up.

We must have, in our daily control records, sufficient data to keep a tight rein on our operations. If results fade we should know immediately so we can correct the situation. If results improve, it is equally important to know why immediately so that we can perpetuate the improvement.

Labor

A second very important influence on the cost of manufacture of lumber and plywood, and on profits, is labor.

Wages per hour in the U.S. and in Canada have been steadily increasing. There are no indications that it will not increase some more. The standards of living in this country have been changing. Central heating, modern plumbing, refrigeration, push-button cooking equipment, radio, television, automobiles, and many other developments unknown 50 years ago have become necessities in our way of life. This change has created new markets. It has spurred industry into undreamed-of activity. It has created a desire for more money on the part of our people, which is very real. Anything that we might attempt to do is not going to change this trend. It has become a way of life in the Western world.

This increase in hourly wage tends to frighten us. We see labor costs going up. We see loss of markets to competitive materials. We see ruin ahead of us. We run to the medicine cabinet for pills, for panaceas. We talk glibly of automation, of increasing the speeds of machines, wage-incentive schemes. We have a strong tendency to panic.

What we should do is roll up our sleeves and go to work.

We have got to change our basic concept of labor. Labor to most of us means hard physical work. It means lifting, carrying, pushing, sweating. All of these functions with modern developments in production lines can be better done with the use of mechanical, electrical, pneumatic, or hydraulic devices.

When we examine our operations in logging, in sawmilling and plywood manufacture, we find that the important thing for which we can find no alternative for human effort is judgment. What trees shall we cut? How shall we cut the tree into logs? How can we get the most quality out of the log at the head saw? What widths will we develop at the edger? What lengths shall we trim the board? Similar questions are raised in the manufacture of veneer and plywood. Once these decisions have been made, the sooner, the easier they are put into execution, the quicker we can get to the next tree, the next log, the next board.

I can remember the old kerosene light. If we wanted a light, we first got the lamp off the shelf. If we had not cleaned it after the last use we cleaned it and trimmed the wick. We then got a match, found some place to strike it, lit the light, replaced the chimney, and then set the light in the desired location. For years since that period I have been getting better light by pushing a button on a conveniently located fixture. The important thing today is the decision to have light. Getting the light is a push-button detail.

In our sawmills and plywood plants, we have many hangovers of the kerosene lamp days. We spend too much time, too much effort, in executing our decisions. The execution of decisions is frequently so difficult, due to the lack of reasonable facilities, that the decision falls by the wayside and we fail to make the profit we should.

Let's sit in an automobile for a while. We have an interesting companion and are holding a conversation. It starts to rain. Without thinking we push on the windshield wiper. It gets colder, we push the heater button. We want to make a turn, we flash the turn signal, take our foot off the accelerator, step on the brake, slow up and make the turn. The signal stops automatically. We step on the accelerator and are off in a new direction. The decisions were all made quickly. The execution, because of the thought, the planning, the engineering and design that went into the car, plus the driver training, was fast and effortless.

We have got to put this same sort of thinking into the woods, the sawmill, and plywood operations. We can't eliminate men at decision points any more than we can eliminate the driver behind the wheel. We can eliminate the necessity of beef and brawn for back-breaking labor, for time in the execution of decisions. We can also provide facilities for better vision, for conveniently placed controls, for eliminating or reducing fatigue.

These things can be done and must be done if we are to face increasing labor rates in a highly competitive market. They are, however, the easiest part of the job. The difficult problem, having reduced the physical effort in logging, sawmilling and plywood manufacture to its proper place in the ec-

re, is to give the operator the proper ols to think with.

What are these tools? Basically they : values and methods of getting lues from a tree or log. Suppose we nit ourselves to the sawmill—the inciples will apply to other depart-ents. The character of material in gs varies in all logs brought in from : woods. There is some clear mate-l and some low-grade or often use-ss material in each log. The problem the sawyer is to reduce this log to ards that have the highest sale value the current market. The greatest reaks in value for a given species are ssociated with grades. Selects and Bet-er birch are worth, roughtly, $300.00 per M., #1 Com.,–$150.00/M, and #2 & #3 Com. worth $75.00/M.

There are, however, other premiums in sawmilling that are important. 8/4 Birch F.A.S. sells for $315.00 a M., 4/4 for $290.00 per M. In addition, increasing the average thickness of lumber improves the volume yield or over-run. Premiums are paid for lengths and widths. Most mills will also cater to certain customers and make special items that are good, profit-wise, for the customer and good for the mill. These basic considerations should be common job knowledge of anyone called on to make decisions in the manufacture of lumber. The values do not have to be current. The crew does not have to study lumber sales prices daily before they operate the mill. They do, however, have to know grades and factors that affect values.

In addition to being conversant with these values, the head sawyer must know, when he sizes up a log, how to get value out of the log. If a hardwood log has one high-grade quandrant, this quandrant should not be divided between two faces. Conversely, a poor quandrant should not be split between two faces, and thus drag the value of both down. Logs with pronounced taper, when reduced to boards of uniform thickness, will yield wedges. These wedges should be made of the lowest grade material in the log. Common practice in hardwood mills is not only to make these wedges out of the best material in the log, but in doing so to reduce the quality of the good lumber produced. Where the edgerman places his saw lines and where the trimmer man places his cuts should be based on values he is producing. We will never have efficient sawmills until we have them manned with operators who will react just as strongly to the loss of value in our manufacture as they would to a man standing at that mill burning up the equivalent in dollar bills.

The increased cost of wages is unquestionably staring us in the face. It means a radical change in our attitude toward labor. We have got to take the backbreaking, time-consuming features out of our mills. We have got to have men in whom we have confidence to make decisions and who have the coordination and dexterity to punch the button or throw the light switch to execute that decision. We in management have two prime responsibilities—we have got to provide labor with 1) the physical equipment, and 2) the tools with which to make decisions. This calls for united effort on the part of equipment suppliers, engineers, maintenance people, supervision, and management to see that our mills are properly equipped and our operators properly trained.

Before passing from this subject of labor I'd like to dwell on one theme for a moment. I've been in this position many times where I have to face the statement "It's a good theory, but it won't work". My comeback is "If the theory is sound it will work". Frequently in development work and in engineering, one has to travel in new fields. He cannot lean on precedent to back his conclusions. The going then is rugged. In this case, however, I would like to describe briefly the situation of sawmilling in the Northwest. The labor scale starts at over $2.00 per hour for an 8-hour day. The mills are a long way from the market. Because of the factor of scarcity, the price of stumpage climbed. Small mills began to fold. Large mills scrambled to add chip plants, particle board plants, plywood operations, and even paper mills, to get a greater sales recovery on their basic raw material—logs. Out of this economic evolution a new factor began to rear its head. Hard-headed, intelligent small operators began to study their operations, and without too much help from outsiders put together the push-button mills. Production figures developed were unheard-of. Quality of manufacture was excellent. They were not too concerned about the wage per hour. They needed men whose judgment they could rely on, not men whose strong backs they could lean on. Out of this source came the riderless carriage, the push-button set works for the edger, and many other significant developments.

The operators had taken off their coats and got to work. That will be our salvation if we survive in the Eastern hardwood region.

Load or Burden

Quite a number of factors go into the development of load or burden. Because of the time factor I would like to touch on only three of them, namely 1) supervision, 2) maintenance, and 3) depreciation.

Supervision is the contact between plant operation and management, between the plant and sales. Supervisors are responsible for the smooth operation of the plant, for the maintenance of standards and of equipment, for safety of the crew, for labor relations. These supervisors, particularly in small organizations, are very important people. With the complications pressed on industry as a result of more government controls, of labor unions, and driving pressing business agents, of directives if he happens to be in a small unit of a large organization, he not only must have a good solution to the problem with which he is confronted, he must have a solution which is compatible with the government, labor, and industrial regulations with which he is surrounded.

Formerly it was the custom to make a supervisor out of a good operator, particularly if he seemed to have an ability to get along with people. We would call him into the office, make him a foreman, tell him to take over, we'd back him, and congratulate him on his promotion. We would also put him on the monthly roll, so that we would not have to bother with overtime. If he was a good man—an awfully good man—he might make the grade. Today his chances of making the grade are even less. The grade is tougher. Able talent shy away from our industry. You can't blame them. The load we put on supervision is heavy. We give them little or no help, and we expect perfection. We probably pay them all we can afford to, the way we run our business. We don't pay them what we will have to if we want to attract the caliber of men we need to run our business at a profit under the social and economic conditions we operate. It would be absurd to leave here, go home, and tell our supervisors they are are all going to get more money. It would make sense to go home, analyse our supervisory responsibilities, and state that when performance reaches certain levels the split for supervision will result in more money for supervisors. If supervision does not measure up, then new talent will have to be hired and trained. Such talent is in demand today -competition is high. Smart, able, young trained men have a habit of candidly evaluating possibilities.

Let's go back a bit and look at certain aspects of our supervisory jobs. Remember that other than for a few perfunctory remarks, we have put a man on a job and said "now you are a supervisor". Let's assume that he is

familiar with the basic information on which the mill is operated:

He must be introduced to the tools of management, which are production reports, cost reports, safety reports, union contracts and agreements.

He must be familiarized with management's policies in hiring and discharge or lay off of men, of handling grievances.

He should have routines carefully and thoroughly explained.

He should be taken into the confidence of management, insofar as his job is affected, on plans for the future.

He should be given an understanding of how his work, his department ties into the work of others and made to feel that his part is an important one in the successful operation of the company.

The amount of money we pay supervision, if we draw the type of people to our industry that we need, will undoubtedly go up. The returns on good supervision, well selected, well trained, and equipped with the proper tools for running their jobs, will often be the difference between profit and loss, success and failure.

Maintenance Factor

The second factor of burden which merits attention is maintenance. Formerly, maintenance was almost the sole province of the millwright. He handled the belts and line shafts, poured the babbit bearings, set the machines, repaired the breakdowns, and generally kept the mill running, sometimes with the assistance of a steamfitter and electrician. Today, maintenance is responsible for equipment loaded with limit switches, relays, tubes, high frequency, all kinds of pneumatic and hydraulic valves, cylinders and controls. Babbit bearings have been replaced with antifriction units, which often are automatically lubricated or are equipped with sealed bearings. No longer is maintenance primarily a millwright job. As we go into mechanization we must make certain that our maintenance crews are not only receptive to the change in the nature of their work, but that they are qualified to handle it.

One common development as we move toward mechanization of sawmills, logging operations, and plywood plants is the changing ratio between direct and maintenance labor. This situation requires constant watching. When we eliminate a low-priced direct employee and find that we have had to put on a high-priced maintenance man, with no improvement in production or quality, we have made no progress. In fact, we have slipped. This factor is so important that when we buy equipment or machines we should check it from a maintenance angle as carefully as we do from an operating angle. If we don't do this, I can assure you that we can find ourselves in some very embarassing positions.

Depreciation Feature

The third and last feature of Load and Burden I would like to touch on is depreciation. It is a rather difficult subject to handle—it depends on the life of the operation, the tax structure, the nature of the capital investment, whether the unit will operate on a one-, two-, or three-shift basis. General practice in forest products industries, where plant investment is high, has been to operate on a two- or three-shift basis. This is pretty near a universal practice in paper mills, and it is true for plywood plants in the Northwest. It is not generally true in sawmills. It may well be that, in sawmills, as we make them smaller, more compact, as we reduce the crews, that we will find it expedient to make a general practice of two-shifting.

Before closing the subject of the cost of production and dwelling briefly on the cost of selling and shipping, I would like to mention one check that is essential in evaluating a new machine, a new process, or new handling equipment. The cost of the new venture should be superimposed on a Profit and Loss statement in order to insure that all factors of costs have been properly evaluated and considered. If the new development does not show up profitably after an honest treatment of this sort, the chances are that you either have more work to do before installation or that you should drop it like a hot potato.

Selling and Shipping Expense

That portion of the cost of sales with which I wish to deal here is the way our product is loaded and graded and how it is shipped to the customer.

The lumber and plywood business is gradually being forced to ship its products to its customers in better shape. It not only has to have quality—it must look like quality. Much of our competition is doing an excellent job along these lines. Our prefinished doors and panels are carefully packaged. Certain plywood panels and lumber items are wrapped before shipment. Just how far this trend will go is problematical. There are two items, however, which I would like to mention. The first is that, as an industry, we have a tendency to forget the value and use of our products. I have personally spent hours intermittently cussing and sanding to remove blue crayon marks from lumber so that I could finish it. I have seen high-grade lumber with dirt from carrier travel splattered all over it. I have seen plywood carried on trucks exposed to weather. I have seen car loaders walking on high-grade pine lumber. Little things—yes, but still important. They mean that there are many men in our mills who don't realize the value of the material they are handling. To the customer, it is a source of irritation that results in claims. Settlement of claims can be a constant leak. They cost money, even though the claim is thrown out.

Most of our lumber today, except on the coast, is shipped either by truck or rail. By rail it is shipped either on open flat cars or box cars. The advent of fork trucks and straddle-truck carriers has brought about radical changes in our yard, drying and storing facilities. Customers are confronted with handling problems as well, and many of them also use fork trucks and straddle trucks. This package handling of lumber has become a very important technique in the lumber industry. The wider the pile of stickered lumber the more stable it is. If we let the pile get too wide, however, we get into trouble. If we exceed four feet we can't spot two loads on a truck side by side. If we use 4-foot-wide piles in one section of the operation and 5-foot or wider in another area, then we have the problem of duplication of equipment. Package handling of lumber is with us. It probably is with us to stay. We have got to analyze our green chain problems, our stacker and unstacker problems, our seasoning and grading problems, our customers' desires and our shipping facilities, and then, and then only, can we set up our handling facilities for keeping costs down.

In conclusion, I would like to reiterate again that we are going through an economic evolution in the forest products industries. With the quality of timber going down, the cost of equipment and labor rates going up, we can't continue in the ways of our forefathers. Our hope lies in taking up the slack that has resulted from the extravagant use of our base material, and failure to use labor efficiently. The taking up of this slack will be made much easier as a result of the technological developments in the material handling, electric, pneumatic, hydraulic, and machinery fields. The effort is not going to be easy. It is going to take the combined effort of all of us, working in the same field, pulling together and helping one another to meet these problems with which we are faced today.

Applying Linear Programming[1]

TO THE PLYWOOD INDUSTRY

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Linear programming techniques provide management with improved information to aid in decisions on log purchases, peeling of veneers, and using the veneers to produce a more profitable product mix. "By-products" of the solutions are "shadow prices", "opportunity costs", and matrix elements.

THE APPLICATIONS of linear programming to the plywood industry, in particular the softwood industry, have recently been studied. This paper discusses the preliminary examination, augmented by actual data wherever possible. The general value of linear programming in these applications having been confirmed by this early study, more extensive work is now being carried out for specific companies.

The studies made have shown that, when costs are expressed in a simple way in terms of some volumetric measure, the very significant contributions of grade and other factors (sanding, glue, and so forth) which depend on surface measure, are hidden. Costs should rather be considered, as in the Mayhew system, in terms of the product specifications and labor content of a plywood panel. The method of extending the cost studies that was sought should therefore provide better rules and guides to aid in management decisions, such as log purchases, veneer production, and product mix. Two of these problems (product mix and log purchases) are treated here, independently of one another, to show how the use of mathematical models can improve the profitability of a plywood manufacturing enterprise. The models demonstrated are somewhat simplified but they are, nevertheless, realistic and lead to meaningful and valuable results. Simpler problems were treated because of the limitations imposed by a small computer, the absence of necessary data for a full-scale calculation, or both. Larger problems are now being investigated for specific companies.

Problem I—Product Mix

Softwood Plywood Production: A mill purchases (or obtains from government or owned land) logs that can be peeled in several thicknesses. Any log yields veneer of 6 or more grades, the percentage yield among grades varying from log to log even when logs of a single grade are peeled to the same thickness. Veneer costs then are subject to a somwhat arbitrary distribution among the various grades (which are the "joint products"). Even the best system of allocating veneer costs, that of assigning costs according to the "realization" on the finished products containing the grade, is subject to merited criticism. Another company using the same logs and peeling in the same way could conceivably have different veneer costs if the product mix were different. Further, the same logs could be peeled differently to obtain still a third set of veneer costs by grade. Since the assignment of veneer costs depends on the final product mix, these costs cannot be used to determine an "optimal" product mix.

Consider the "X Plywood Company." In 1956, this company produced 44 products in the quantities listed in Table 1. Each final product required three or more sheets of veneer of the following grades and thickness:

Thickness	Grades used[1]
1/10"	A, B, C, D, Cx, Dx
1/8"	A, B, C, D, Cx, Dx
3/16"	C, D, Cx, Dx

[1]The subscript x indicates crossband.

Assume that the available logs give the mixture of grades and sizes required for the listed quantities of final product. The available veneer supply is fixed; it is listed in Table 2. Since we cannot justify costing veneer by grade and thickness, we cannot calculate a profit per unit of product. Instead we shall use "return" as a measure of profitability. "Return" is defined as the selling price minus standard trade discounts and those cost contributions (other than veneer) which are product-dependent (labor, glue, and so forth). The problem can then be expressed in the following way:

> "Which product and how much of each should be produced from a known distribution of veneers of various grades and thicknesses so that the return is maximized?"

It must be tacitly assumed that we can market any products manufactured without further discounts. This latter assumption will be modified later.

Now, an A grade sheet of a given thickness can be used for any product that requires the A grade sheet. The amount of A grade sheets is limited; if we use the sheets for AD panels, we restrict the possible production of AA, AB and AC panels. Similarly the use of Dx sheets in AD panels restricts the possible production of other products requiring the Dx sheets of the same thickness. Hence all product are intimately connected. These restrictions can be expressed mathematically in a simple form, and the resulting mathematical equations can be manipulated by the method of linear programming.

Let X_i be the fraction of product i produced (for example $i = 17$ indicates AA 1/4 inch Interior, $i = 18$ indicates AA 3/8 inch Interior . . . $i = 56$ indicates CC 5/8 inch Exterior), and b_j be the fraction of veneer j available ($j = 1$ indicates A 1/10 inch, $j = 2$ indicates B 1/10 inch, . . . $j = 16$ indicates D_x 3/16 inch). Now, the total production requiring j grade veneer cannot exceed the available quantity of that veneer, or

TABLE I PRODUCTION OF PLYWOOD PANELS IN S.M.

GRADE AND SIZE		X COMPANY	AVERAGE COMPANY
AA Interior	1/4"	49,300	388,200
	3/8"	65,500	117,000
	1/2"	139,400	208,500
	5/8"	49,700	58,900
	3/4"	996,800	1,052,000
BB Interior	1/4"	30,000	300,000
	3/8"	53,100	108,100
	1/2"	478,500	438,400
	5/8"	118,800	150,900
	3/4"	1,175,000	1,704,800
AD Interior	1/4"	8,017,700	10,502,800
	3/8"	1,085,900	2,468,000
	1/2"	1,332,000	3,159,400
	5/8"	784,100	1,432,200
	3/4"	1,798,800	1,879,100
CD Interior	5/16"	324,500	2,962,400
	3/8"	1,031,300	1,993,900
	1/2"	1,771,800	1,393,700
	5/8"	1,441,400	1,132,900
	3/4"	78,300	1,900,300
AA Exterior	1/4"	133,400	149,700
	3/8"	72,500	87,400
	1/2"	48,800	83,900
	5/8"	8,000	10,000
	3/4"	47,100	43,900
AB Exterior	1/4"	13,600	98,100
	3/8"	47,400	130,500
	1/2"	74,400	198,600
	5/8"	17,300	40,800
	3/4"	47,000	17,900
AC Exterior	1/4"	2,945,500	3,707,100
	3/8"	3,180,400	4,741,300
	1/2"	901,300	1,991,100
	5/8"	74,300	411,500
	3/4"	1,000,400	1,133,400
BB Exterior	1/4"	116,500	69,100
	3/8"	-	13,300
	1/2"	30,700	12,500
	5/8"	47,400	389,100
	3/4"	312,300	154,100
CC Exterior	1/4"	58,100	188,400
	3/8"	137,400	338,800
	1/2"	8,900	345,400
	5/8"	148,000	460,400
	3/4"	9,400	44,200

TABLE II VENEER AVAILABLE IN S.M.

GRADE AND THICKNESS		X COMPANY	IN DECIMAL FRACTION	AVERAGE COMPANY	IN DECIMAL FRACTION
1/10"	A	9,781,000	.0786	15,750,000	.055
	B	683,000	.0055	803,000	.002
	C	6,021,000	.0484	15,086,000	.052
	D	10,804,000	.0868	28,059,000	.098
	Cx	5,897,000	.0474	8,425,000	.029
	Dx	12,998,000	.1045	32,520,000	.113
1/8"	A	15,776,000	.1268	28,119,000	.098
	B	5,179,000	.0416	12,938,000	.045
	C	9,464,000	.0761	22,655,000	.079
	D	12,011,000	.0965	33,710,000	.117
	Cx	1,962,000	.0158	5,735,000	.020
	Dx	7,877,000	.0633	17,549,000	.061
3/16"	C	2,581,000	.0207	7,016,000	.024
	D	5,656,000	.0455	11,636,000	.040
	Cx	7,108,000	.0571	13,387,000	.046
	Dx	10,636,000	.0854	27,742,000	.097
TOTAL		124,430,000	1.0000	286,130,000	1.000

TABLE III IDEAL SOLUTION FOR X PLYWOOD COMPANY

		Run	Per Cent				Run	Per Cent
Interior	AA 1/4	-	-	Exterior	AA 1/4	-	-	-
	AA 3/8	-	-		AA 3/8	-	-	-
	AA 1/2	-	-		AA 1/2	-	-	-
	AA 5/8	-	-		AA 5/8	-	-	-
	AA 3/4	-	-		AA 3/4	-	-	-
	AD 1/4	-	-		AB 1/4	-	-	-
	AD 3/8	-	-		AB 3/8	-	-	-
	AD 1/2	-	-		AB 1/2	-	-	-
	AD 5/8	-	-		AB 5/8	-	-	-
	AD 3/4	-	-		AB 3/4	-	-	-
	CD 5/16	-	-		AC 1/4	-	-	-
	CD 3/8	-	-		AC 3/8	-	-	-
	CD 1/2	-	-		AC 1/2	-	-	-
	CD 5/8	-	-		AC 5/8	-	-	-
	CD 3/4	-	-		AC 3/4	-	-	-
	BB 1/4	-	-		BB 1/4	-	-	-
	BB 3/8	-	-		BB 3/8	-	-	-
	BB 1/2	-	-		BB 1/2	-	-	-
	BB 5/8	-	-		BB 5/8	-	-	-
	BB 3/4	-	-		BB 3/4	-	-	-
	CC 1/4	-	-		CC 1/4	-	-	-
	CC 3/8	-	-		CC 3/8	-	-	-
	CC 1/2	-	-		CC 1/2	-	-	-
	CC 5/8	-	-		CC 5/8	-	-	-
	CC 3/4	-	-		CC 3/4	-	-	-

$$(1)\quad \sum_j a_{ij} X_i \geq b_j$$

where a_{ij} is the number of sheets of j grade veneer required for product i. For example, $a_{17,1} = 2$, means two A 1/10 inch sheets are required for each panel of AA 1/4 inch; $a_{18,1} = 2$, two A 1/10 sheets are required for each panel of AA 3/8 inch, $A_{56,1} = 0$, no A 1/10 inch sheets are required for CC 5/8 inch.

There are 16 such requirement equations connecting the 40 to 45 product variables. These equations plus one more

$$(2)\quad Z = \sum_i R_i X_i = \text{Maximum},$$

define the problem. Here R_i is the return on the i^{th} product. In effect equation (2) states that we want to maximize the return on the available raw materials. The return on all products is listed in Table 3.

Solution of linear programming problems of this order are time-consuming if done by hand. Solutions have been obtained on the IBM 650 computer (using a modified H. Smith program) in about 30 minutes of machine time. The solutions show that considerable savings are possible. For "X Plywood Company" we find the return (per 1,000 S.M. of veneer) is $22.47; this is to be compared with $21.16 obtained from their actual production. The difference, $1.31, when applied to the annual production of about 120,000,000 Surface Measures of veneer could result in increasing the return by about $150,000 per year. The bulk of the increase in return is profit, because the fixed costs will be practically unaffected by changes in the product mix. The form of the results of the linear programming computation is shown in Table 3. The "ideal" solution calls for the production of only the 15 products listed here:

Interior grades: AA 3/4, AD 2-AD 5/8, CD 5/16, CD 3/8, CD 1/2, CD 3/4.

Exterior grades: AA 1/4, AA 3/8, AA 3/4, AB 1/2, AC 3/8, BB 1/2, BB 3/4, CC 3/8.

The production of any other items must lead to a reduction in return.

hese reductions can be discussed in rms of the third column of Table 3 arked "Shadow prices." The shadow rice is the loss in return per 1,000 M. of plywood panels produced since this can only be produced by ducing the production of at least one the ideal products) In this case, e production of 1,000 S.M. panels interior AA 1/4 inch. would produce loss in return of $22.42 while the oduction of 1,000 S.M. of exterior B 3/8 would only produce a loss in urn of $1.55. The value of the adow prices is that they allow one determine how the return is affected deviation from the "ideal" product ix.

The "solution" of the problem consists of more than the quantities to be produced and the shadow prices. We also obtain a matrix or table of numbers that shows the best way (that is, the cheapest) to introduce a product not included in the basic solution. This is demonstrated by example later. Further, by using the shadow prices we can determine if a new product is profitable or if it is profitable to make an established product in another manner.

The solution here is not completely practical in that market restrictions have been ignored. For example, about 11 per cent of production is interior AA 3/4. The market for this product is relatively small. Similarly, there is no production of exterior BB 5/8, which is a popular product. These restrictions can be incorporated in the original set of equations, in which case we would have found a different solution (and, of course, a lower value of the return). We can, however, within a fairly wide range use the shadow prices and the final "matrix" to determine the effect of modifying the production. For example, our solution results in an excess of 2.6 S.M. of 1/10 inch D veneer per 1,000 S.M. of initial product. This could be used as 1/10 inch Dx and give a slight increase in our return (increased by $23.60 x 0.0026 = $0.06, making the return $22.53).

The value of $23.60 is the shadow price associated with 1/10 inch Dx veneer. The shadow price of the raw material is the added return that can be obtained if there were an additional 1,000 S.M. of the raw material available. These shadow prices are indications of how peeling can be modified in order to produce greater returns, or how one might improve the return by changing the quantity peeled in each thickness. A study of Table 3, for example, shows that D_x has a greater shadow price than D for all thicknesses. In an actual problem a result of this form would indicate that downgrading D to D_x may be profitable. A large difference in shadow price between B and C grades would indicate that more labor on patching grade C to B might be profitable. The differences in shadow prices also give indications of changing the peeling distribution.

Table 4 shows the solution obtained for the "Average Company." The "ideal" return for the Average Company is $21.22 as compared with the actual return of $20.08 per 1,000 S.M. of veneer. We obtained $.2504 units of product for each unit of veneer. This is a difference of $1.14 per 1,000 S.M. of veneer produced. The ideal production for this company differs from the previous example for two reasons: (1) the return (and cost) structure is different (Tables 3 and 4) and (2) the raw product mix is different (Table 2). X Company uses logs that yield more A and B grade and also peel more 3/16 inch, hence the greater return.

We can examine the changes implied by altering the production. Let us assume that we must produce interior AB 3/4 inch (product 26). To do this we must change our production of other products. The final matrix for product 26 gives the values shown in Table 5, Column 1. The values show that, for each unit of product 26 produced, the output of product 40 is increased by 0.5 units, the output of product 52 is reduced by 0.5 units, and the output of product 21 is reduced by 1.0 unit. (A plus sign in the matrix column indicates a reduction and a minus sign indicates an increase). For each 1,000 S.M. so changed, the shadow price tells us that we will lose $6.47 in return. If we do this for 4 per cent of production our return will be reduced by (0.04) x (0.2504) x 6.47. (0.2504 is the number of 1,000 S.M. panels produced

TABLE IV SOLUTION FOR AVERAGE PLYWOOD COMPANY

			Per Cent of Total Production	"Shadow Price"	"Return"	Raw Materials	Int...
Interior AA	1/4	17	-	$10.57	$ 81.1[illegible]	A	$39.9[illegible]
	3/8	18	-	8.31	101.[illegible]	B	26.34
	1/2	19	-	.65	120.34	1/16" C	21.65
	5/8	20	-	2.21	132.99	D	11.45
	3/4	21	-	3.09	151.67	Dx	10.31
							11.90
B	[illegible]		-	10.70	97.4[illegible]	A	42.87
	3/8	[illegible]	-	8.11	94.[illegible]	B	26.39
	[illegible]	[illegible]	.0682	-	1[illegible]	C	20.87
	5/8	[illegible]	.0757	-	118.42	1/8" D	14.61
	3/4	26	-	2.97	135.00	Cx	19.48
						Dx	14.01
AD	1/4	27	-	9.71	53.56		
	3/8	28	-	7.85	73.42		
	1/2	29	-	.18	92.55	C	19.30
	5/8	30	.1023	-	106.95	D	21.43
	3/4	31	-	2.63	123.87	3/16" Cx	28.15
						Dx	[illegible].79
[illegible]	5/16	[illegible]	.0980	-	[illegible]		
	3/8	33	.0105	-	43.[illegible]		
	1/[illegible]	34	.1315	-	[illegible]		
	5/8	35	.0273	-	77.[illegible]		
	3/4	36	.1739	-	97.[illegible]		
[illegible]erior	1/4	37	.1[illegible]	-	90.1[illegible]		
	3/8	38	.01[illegible]	-	113.89		
	1/[illegible]	39	-	.84	127.18		
	3/4	40	.0808	-	161.97		
[illegible]	1/4	41	-	.49	76.[illegible]		
	3/8	42	-	1.9[illegible]	95.1[illegible]		
	1/2	43	.0911	-	111.[illegible]		
	3/4	44	-	-	146.89		
[illegible]	1/4	45	-	12.08	59.80		
	3/8	46	-	8.92	82.37		
	1/[illegible]	47	-	5.[illegible]3	99.78		
	5/8	48	-	6.3[illegible]	116.71		
	3/4	49	-	5.39	134.98		
[illegible]	1/4	50	.0061	-	62.99		
	5/8	51	.0101	-	111.[illegible]		
	3/4	52	.0163	-	1[illegible].4[illegible]		
	1/4	53		[illegible].14	[illegible].47		
	3/8	54	.0674	-	60.0[illegible]		
	1/[illegible]	55	-	4.9[illegible]	80.[illegible]		
	5/8	56	-	8.91	91.7[illegible]		

TABLE V

Matrix	Item (Per Cent of Production)	Matrix	Item
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Interior [illegible]		
	CD	.1099	.1099
	Exterior [illegible]		
	BB		
	Interior [illegible]		
	CD 5/16"		
	Exterior [illegible]		
	A		
	[illegible]		
	[illegible]		
	Exterior [illegible]		
	[illegible]		
	[illegible]		
	[illegible]		
	Interior [illegible]		
	[illegible]		
	[illegible]		
	[illegible]		

per 1,000 S.M. of veneer.) Thus the return is reduced by about six cents per 1,000 S.M. of veneer.) Column 3 of Table 5 shows the final production if this change is made.

We can make further modifications based on the information generated by our final matrix. Suppose that in addition to interior AB ¾ inch we must produce exterior BB ⅝ inch (product 51). The 5th column of Table 5 shows the final matrix column for product 51. Each unit of product 51 produced results in an increase of 1 unit of product 38 and a decrease of 1 unit each for products 46 and 40. Now, since we only produce 1 per cent of product 46, we cannot produce more than 1 per cent of exterior BB ⅝ inch (or else we would have a "negative" production). If we produce 1 per cent of exterior BB ⅝ inch we end up with the production listed in the last column of Table 5. The return is reduced by (0.01) x (.2504) x 17.59 = 0.04.

The process can be carried on to include as many essential products as necessary. This substitution process is extremely useful for determining the return for various combinations of production. The changes made in production quantities are those which would introduce the products at minimum loss in return. The alternative to this method is the re-evaluation with added market condition equations. The program can be set up so that the effect of price changes can be treated starting from an existing solution. The latter requires much less computer time for the new calculations. One can define condition equations for the size of price change necessary to require a new solution. The method is extremely flexible to almost all possible changes.

The example shown here illustrates that improved production performance is possible. The tables also show the data for an "Average Company," the data for which has been generated from a cost study of some dozen companies for 1957. The results for the average company show savings of the same order of magnitude as the example company. We have carried out other calculations with the same sort of results. In our calculations, we were restricted somewhat by the available data and more by the restrictions in the computer program. Because of the latter limitation we only considered 41 final products. A more extensive program for the IBM 650 is available that will allow about 55 products and 20 raw material and market restriction equations. For larger-scale problems, the IBM 700 series, the UNIVAC, DATATRON, and other computers are available. If such machines, are used there would be no need to omit such factors as sales potential, interchangeability of raw materials, alternate methods of making the same final products, and so forth.

Hardwood Plywood Production: No thorough analysis of hardwood plywood production has been made thus far. The differences between hardwood and softwood production are those of complexity and variety rather than differences in principle. In hardwood, one deals with a number of varieties of wood in a range of grades rather than a single variety. Logs are also purchased in a greater multiplicity of log grades. The complexity introduced by the numerous varieties and grades, and the fact that the products and veneers have much higher values, makes the selectivity, that is, the decision on product mix, a more critical problem.

The basis of any analysis of production mix, by purchases, veneer peelings, and so forth, is a good cost system. Without knowledge of the costs of various alternatives one can make only rough guesses as to the relative value of a given production, peeling or purchasing policy. Such cost systems are not firmly established in the hardwood industry and examples are therefore hard to come by. We shall, however, discuss the application of linear programming methods to a number of possible problems in the manufacture of hardwood panels.

First, let us consider the softwood producer who also manufactures hardwood panels with softwood centers. The hardwood panels "compete" for softwood centers and cores and thus interact with all the softwood products. If a C_x core is used for ⅝ inch AC Exterior panel it is not available for a ¾ inch Birch panel; a B grade center used for a hardwood panel restricts the production of AB and BB products that require the same thickness sheet of veneer.

Assuming that the variable costs of hardwood panels are known, we can treat the hardwood panels in the same way as other products. We shall consider two cases.

1. Hardwood veneer purchased outside and no limit on available supply (that is, a free market with adequate sources of veneers).

In this case the problem can be set up in the same way as problem 1. The various hardwood products are introduced only through the softwood components of the layups. The return on a hardwood product is defined as

R_i = (Selling price) — (discounts)—(variable costs of manufacture)—(cost of the hardwood veneers).

2. Hardwood veneers manufactured by the company or purchased in a restricted market (that is, the quantity of hardwood veneer in each grade is limited).

This case differs from the example above in that the hardwood panels "compete" for both softwood and hardwood components. If the hardwood veneers are purchased, then the return R_i is as defined above. If hardwood veneers are manufactured, then we use the earlier definition of R_i given in problem 1. In both cases one must introduce the hardwood components of the layups in establishing the matrix. We will then have equations of the form of Eq. (1) for the hardwood veneer supply as well as for the softwood veneer supply. The hardwood products may also be included in or subject to market restrictions of the same form as have already been presented.

Thus, the introduction of hardwood veneers and panels does not alter the problem in any serious manner, when one is concerned with the production of combined hardwood and softwood panels. One would expect this to be true, since the production method is similar and the interactions are not different in principle. In fact, the principles are even much the same for plants which produce entirely hardwood panels, as we shall show.

Let us now consider a company that produces only hardwood panels from a number of different species (oak, birch, maple, white pine, lauan, and so forth). Centers and cores are obtained from the hardwood (or perhaps by purchases of softwood panels or veneers). As in the softwood case, there are a number of different raw materials (veneers by species, grade and thickness) obtained by peeling logs. These are to be used to produce plywood panels of various thicknesses and quality in such a way as to maximize profits, subject to the limitations of marketability of products, plant capacity and other plant restrictions. One can set up a layup and restriction "matrix" just as in the case of softwood production. Because of the larger variety of raw materials (veneers) and finished products one will have a "larger" problem for a single plant. While limits the size of the problem is no obstacle, problems involving a number of integrated plants in one system are already being studied. Given a good cost system, this problem can be treated quite readily and perhaps yield even greater increases in return that in softwood production because of the higher costs of peeling and grading in the hardwood industry.

Problem 2—Log Purchases

In the previous example, we were concerned with obtaining the best mix of final products from a group of sheets of veneer. This is equivalent to obtaining the best product mix from a group of logs. The connection lies in the relationship between grades produced from a log of given quality. A study made by the U. S. Forest Service[2] indicates that such relations exist. For Southwest Oregon the report gives the results below.[3]

Log Grade	% A Veneer	% B Veneer	% C Veneer	% D Veneer
#1 peeler	37	11	32	20
#2 peeler	28	9	33	30
#3 peeler	17	8	34	41
Special peeler	8	7	44	41

Given these values and a panel recovery ratio (panels ⅜ inch equivalent per board foot of lumber) we can evaluate the number of sheets of veneer of each grade from the logs purchased. The DFPA Manual lists an average industry recovery ratio of 2.2. Converting this to ⅛ inch equivalent veneer we have a veneer recovery ratio of 6.6. We can use the figure above in an example to show how the logs purchased tell us what veneer is available and the average cost per 1,000 board feet.

Suppose we purchase 1,000, 1,000, and 2,000 M board feet of #1 peeler. #3 peeler, and special peeler, respectively. The number of M ⅛ inch sheets obtained in A grade is

$$(1{,}000 \times 0.37 + 1{,}000 \times 0.17 \div 2{,}000 \times 0.08)\ 6.6 = (370 + 170 + 160)\ 6.6 = 4{,}620 \text{ M sheets of } \tfrac{1}{8} \text{ inch A.}$$

Similarly, we have

$$6.6\ (1{,}000 \times 0.11 + 1{,}000 \times 0.08 + 2{,}000 \times 0.07) = 2{,}178 \text{ M sheets } \tfrac{1}{8} \text{ inch B,}$$

$$6.6\ (1{,}000 \times 0.32 + 1{,}000 \times 0.34 + 2{,}000 \times 0.44) = 10{,}614 \text{ M sheets } \tfrac{1}{8} \text{ inch C,}$$

$$6.6\ (1{,}000 \times 0.20 + 1{,}000 \times 0.41 + 2{,}000 \times 0.41) = 9{,}438 \text{ M sheets } \tfrac{1}{8} \text{ inch D.}$$

If, for the log cost, the listed values for the Example Plywood Co. in the DFPA Manual, are used:

#1 peeler	$90/M bd. feet
#2 peeler	$80/M bd. feet
#3 peeler	$70/M bd. feet
Special peeler	$53.72/M bd. feet

we obtain for the average log cost/m board feet

$$\text{Average cost} = \frac{1{,}000 \times 90 + 1{,}000 \times 70 + 2{,}000 \times 53.72}{4{,}000} = \$66.86/\text{M bd. feet.}$$

Recognizing the fact that the purchased logs define the distribution of veneer by grades (assuming, at this stage, no substitution of one grade for another), we can define the second problem:

> "Given a distribution of final products (and hence the required number of veneer sheets in each grade), what is the best combination of logs to purchase; that is, how many #1 peelers, #2 peelers #3 peelers, and special peelers should be purchased?"

Therefore, this problem is just the reverse of the first problem that was treated by linear programming techniques.

Assume that we want to satisfy the demands for 1/10 inch veneer listed in Table 6. For 1/10 inch veneer the veneer return ratio is 8.25 (6.6/0.8; see DFPA Manual). The log prices are those given previously and we want to minimize the cost of logs to meet our demands. Let P_1 be the quantity of #1 peeler, P_2 the quantity of #2 peeler, P_3 the quantity of #3 peeler, and P_4 the quantity of special peeler. We need 10,591 M sheets of 1/10 inch A. Then:

$$8.25\ (0.37P_1 + 0.28P_2 + 17P_3 + 0.08P_41) \geqq 10{,}591$$

$$\text{(A) or } 3.069P_1 + 2.32P_2 + 1.40P_3 + 66P_4 \geqq 10{,}591$$

Similarly, for the other grades we obtain

$$\text{(B) } 0.91P_1 + 0.74P_2 + 0.66P_3 + 0.58P_4 \geqq 627$$

$$\text{(C) } 2.64P_1 + 2.72P_2 + 2.81P_3 + 3.63P_4 \geqq 11{,}905$$

$$\text{(D) } 1.65P_1 + 2.48P_2 + 3.38P_3 + 3.38P_4 \geqq 25{,}531$$

(Note: In the absence of more complete data we have lumped the requirements for C and Cx and D and Dx.) We want to minimize the total cost of logs: that is, find the values of P_1, P_2, P_3, and P_4 which satisfy equations (A), (B) (C), and (D) and minimize the cost K given by

$$\text{(E) } K = 90P_1 + 80P_2 + 70P_3 + 53.72P_4.$$

This, too, is a problem in linear programming that is solved more simply by using the so-called "dual"[4].

TABLE VI AVERAGE PLYWOOD COMPANY
1/10" VENEER IN PRODUCTS USING ONLY 1/10" VENEER (IN 1,000 S.M.)

GRADE	
A	10,591
B	627
C	7,938
D	12,318
Cx	3,967
Dx	13,213

Because of the small amount of B required, any solution of the problem as stated must result in an excess quantity of B. Since A can be (and often is) downgraded to B grade, and in most cases there is an excess of C grade, we will solve a simpler problem; that is, consider only two grades, A^1 = surface grade, either A or B, and C^1 = back grade, either C or D. In this case our equations become

$$(A^1)\ 3.97P_1 + 3.06P_2 + 2.06P_3 + 1.24P_4 \geqq 11{,}218$$

$$(C^1)\ 4.29P_1 + 5.20P_2 + 6.19P_3 + 7.01P_4 \geqq 37{,}436$$

$$(E^1)\ K = 90P_1 + 80P_2 + 70P_3 + 53.72P_4.$$

Our solutions are

$P_1 = 1{,}435$ M bd. feet,

$P_2 = 0$

$P_3 = 0$

$P_4 = 4{,}535$ M bd. feet.

the total cost is

$$K = \$368{,}500$$

and the average lumber cost is

$$\text{Average cost} = \frac{368{,}500}{5{,}970} = \$61.80/\text{M bd. feet}$$

If more A^1 grade is used, the average cost will increase; the average cost increases with increasing ratio of $A^1/(A^1 + C^1)$ and decreases with increasing ratio of $C^1/(A^1 + C^1)$. We can illustrate this with another example drawn from the data for the

[2] U. S. Forest Services, Report R-6, "West Side Plywood-Lumber Appraisal Base," Table 8, October 22, 1957)

[3] The results are the average for large and small logs rounded off to the nearest percent.

[4] For technical reasons we cannot follow the same techniques as in the previous example. We make use of the fact that every minimizing problem has a "dual" which is a maximizing problem. The solutions are related in a simple manner and the total cost is identical for the problem and its dual. See, for example, Gass, S., Linear Programming, McGraw-Hill, New York (1958).

Example Plywood Company (DFPA Manual).

The total requirements of 1/10 inch veneer are listed in Table 7 (these include 1/10 inch with 1/8 inch and 3/16 inch veneer). In this case, the equations are

$$(A^1, 1/10)\ 3.97P_1 + 3.06P_2 + 2.06P_3 + 1.24P_4 \geqq 11{,}218,$$
$$(C^1, 1/10)\ 4.29P_1 + 5.20P_2 + 6.19P_3 + 7.01P_4 \leqq 49{,}437,$$

$(E^1, 1/10)$ remains unchanged. The solution is

$P_1 = 750$ M bd. feet $\quad P_3 = 0$
$P_2 = 0 \quad\quad\quad\quad P_4 = 6{,}570$ M bd. feet

TABLE VII AVERAGE PLYWOOD COMPANY

TOTAL VENEER PRODUCTION BY SIZE AND GRADE

GRADE	1/10" VENEER IN 1,000 S.M.	1/10" 1,000 BD. FEET	1/8" VENEER IN 1,000 S.M.	1/8" 1,000 BD. FEET	3/16" VENEER IN 1,000 S.M.	3/16" 1,000 BD. FEET
	Factor 8.85		Factor 6.6		Factor 4.4	
A	10,891	1,283.76	20,706	3,137.87	-0-	
B	647	76.30	14,761	2,236.51	-0-	
C	9,347	1,132.97	15,052	2,310.93	7,278	1,654.9
D	15,000	1,818.18	17,535	2,656.81	7,667	1,742.
Cx	6,784	822.30	8,815	1,335.61	20,873	4,471.
Dx	15,903	1,818.24	11,814	1,790.00	15,90	3,47
TOTAL	60,652	7,351.75	88,883	13,467.73	51,108	9,34

The total cost is

$$K = \$432{,}000,$$

and the average cost is

$$\text{Average cost} = \frac{432{,}000}{7{,}320} \text{ or } \$59.00,$$

about $2.80 less per M bd. feet.

We have examined the solutions for the other thicknesses. Since there is no 3/16 inch surface grade (A or B), one can use only special peelers. There will be considerable downgrading, that is 15 percent of the output is surface grade that will be used as C grade, and some of the C grade will be used as D grade, but the average price is not affected. For 3/16 inch the average cost is therefore $53.72/M bd. feet.

The 1/8 inch veneer differs from the 1/10 inch in that a large percentage of surface grade is required—about 40 percent. This must increase the cost of logs and hence the cost of veneer. For 1/8 inch veneer, the veneer recovery ratio is 6.6 and, using the data from Table 7, we get

$$(A^1\ 1/8)\ 3.17P_1 + 2.44P_2 + 1.65P_3 + 0.99P_4 \geqq 35{,}450$$
$$(C^1\ 1/8)\ 3.43P_1 + 4.16P_2 + 4.96P_3 + 5.62P_4 \leqq 53{,}450$$

Equations E^1 remains unchanged. The solutions are

$P^1 = 10{,}250$ M bd feet $\quad P_3 = 0$
$P_2 = 0 \quad\quad\quad\quad P_4 = 3{,}200$ M bd. feet

The total cost is

$$K = \$1{,}119{,}000$$

The average cost is

$$\text{Average cost} = \frac{1{,}119{,}000}{13{,}450} = \$83{,}00/\text{M bd. feet}$$

Thus the lumber costs of 1/8 inch veneer are almost 50 percent more than those of 1/10 inch veneer. This is not surprising, since in 1/8 inch 40 percent of the veneer is surface grade, while only 17 percent of the 1/10 inch veneer is surface grade. It does suggest, however, that wherever possible alternate layups be used (assuming, of course that the veneer used for the products by the Average Plywood Company represents exactly what is desired for a customer and/or profit point of view) such that 1/10 inch surface grade sheets replace 1/8 inch sheets and the thicker sheets be of the lower grades.

For the total veneer supply we have the following results[5]

	1/10 inch	1/8 inch	3/16 inch
Total veneer required	60,104	88,883	41,109
Logs used (M bd. feet)	7,285	13,467	9,343
Average cost of logs (per M bd. feet)	$59.00	$83.00	$53.72

$$\text{Average lumber cost} = \frac{7{,}285\ (59.00) + 13{,}467\ (83.00) + 9{,}343\ (53.72)}{7{,}285 + 13{,}467 + 9.434} = \frac{2{,}049{,}481.96}{30{,}095}$$

Average log cost = $68.10/bd. feet.

The application of linear programming to the log purchase problem is more limited than in problem 1 above because;

(1) There is a relatively small "free" market in logs; purchases are mainly by contract for a tract;

(2) There has been far too little analysis for grade recovery from logs of various grades; more precise data, including the variations in grade recovery by thickness of peeling, are required.

Should the second restriction be overcome, the linear programming technique can provide a measure of the recovery value of a timber tract, given good survey values.

Conclusions

The value of linear programming to plywood enterprises extends beyond providing the solutions to specific problems. As by-products of the solution, the technique generates information on such decision-factors as:

(1) The cost or loss in return due to a capacity or market restriction and hence the value of new equipment or extended sales promotion (of specific products) which would cancel the restrictions.

(2) The cost of producing certain "unprofitable" products to satisfy demands or enter a market. These costs may be too high to merit retention of the customer or the market.

(3) The additional return that might be obtained by changing the peeling distribution or by changing the log distribution.

(4) The profitability or loss (in terms of production costs) of adding new products to the line or changing the layup for an existing product.

(5) The cost of minor adjustments to the ideal product mix and the range in which changes can be made without changing the total return.

(6) The effects of price changes or production costs on the product mix and on total realization.

All of these factors are of great importance to production and sales management. The existence of this information (which is not at present available in most companies) enables better operating and marketing decisions to be made. It is, in fact, possible that the availability of such information will prove of even greater value to the plywood manufacturer than actual solutions that linear programming can provide.

[5] The solutions are given in rounded-off numbers obtained from sliderule calculations. The values listed here are from Table 4.

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"ONE MAN" MODEL E SIDE FEED ELECTRONIC EDGE GLUER

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